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Analysis of the DiveTracker acoustical navigation system for the NPS AUV

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ANALYSIS OF THE DIVETRACKER ACOUSTICAL NAVIGATION SYSTEM FOR THE NPS AUV

by

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ANALYSIS OF THE DIVETRACKER ACOUSTICAL NAVIGATION SYSTEM FOR THE NPS AUV

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ABSTRACT

Autonomous Underwater Vehicles (AUVs) require an accurate navigation system for operating in mine fields located in the near surf zone very shallow water. This research project examined the precision, performance characteristics, and reliability of a low cost, commercially produced, acoustical navigation system called "DiveTracker". The DiveTracker acoustical navigation system provides both an acoustical short baseline operator and the AUV with position data on a 1 hertz update rate. Experiments conducted on the DiveTracker system included static and dynamic tests which examined the system's ability to accurately measure distances and track a moving AUV under water.

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I. INTRODUCTION

A. BACKGROUND

The current emphasis within the U.S. Navy on littoral warfare as outlined in the Department of the Navy 1992 publication "...From the Sea" has brought about many new challenges to the fleet. Amphibious operations in littoral areas face several threats including mine warfare. Underwater mines are a relatively inexpensive weapon which are easily deployed in key areas of the ocean. As seen recently in the Persian Gulf War, a mine field sown at sea, near vital beach-heads, can seriously impair or prevent the landing of amphibious forces ashore. Underwater mines are difficult to detect and even more difficult to clear without seriously endangering naval assets. The damage that can be done by mines is tremendous, as seen in the case of the U.S.S. Samuel B. Roberts (FFG-58), in which a multi-million dollar naval vessel was crippled by a single, low cost sea-mine.

To overcome this silent weapon in waiting, the Naval Postgraduate School (NPS) Mechanical Engineering Department has been researching the feasibility of using Autonomous Underwater Vehicles (AUVs) to find underwater mines in very shallow water (vsw) near-surf zone. The near surf zone (vsw) is defined as the very shallow water area just outside the beach surf where depths range from 10 to 30 feet. Currently, mines sown in this area must be found and cleared by navy divers - a very dangerous and time consuming evolution. In order to launch a beach assault, these mines may have to be cleared for an amphibious force to come ashore from the sea, and ideally, in a clandestine fashion.

The NPS Phoenix II Autonomous Underwater Vehicles is a miniature submarine (about six and a half feet long) which can operate for about three hours under water, untethered, and without direct human input. It provides a clandestine mine reconnaissance capability. AUVs have many potential advantages for mine warfare; they can be deployed from a mother ship which is outside the mine field, hence lessening the danger to the naval vessel. AUVs can also operate unmanned and independent of direct human interface, therefore removing the threat of human casualties which are associated with conventional mine clearance methods.

B. CURRENT ISSUES

Autonomous Underwater Vehicles present potential solutions to many challenges in undersea research found in both civilian and military communities. Commercial missions expected to become viable in the near future include environmental research, under water inspection of off shore oil rigs, and geological ocean surveys, to name just a few [Ref. 1: p.1]. However, AUV technology is still in its infancy. One of the current issues identified by researchers as a critical feature involving control technology is the navigation of AUVs in the underwater environment [Ref. 1]. An AUV which is designed to search, locate, identify, and record the position of underwater mines requires a very accurate navigation system. Mines that are detected must be mapped precisely so they can be located on a positional grid for later reacquisition and disposal. This type of AUV mission demands position accuracy to within distances of less than a meter in order to avoid accidental detonation of the detected explosive device.

The recent developments in the Global Positioning System (GPS), which is based on a satellite radio transmitting system, provides the desired accuracy required for mine hunting AUV missions. Unfortunately, GPS has only limited use in AUV navigation because the high frequency waves transmitted from GPS satellites can not travel underwater. Another navigation system which is used on the U.S. Navy submarines is the Inertial Navigation System (INS). However, this form of navigation provides precise navigation data at tremendous expense. Accurate INS systems that have the precision required for mine hunting missions are not only costly but also complex and bulky. Since a mine-hunting AUV is, by it's very nature, at risk of destruction from the mines that it seeks to locate, a low-cost navigation system is more desirable.

Hence, AUV navigation studies have turned to acoustical systems to provide a reasonably inexpensive and accurate positioning system. Carof (1994) outlined the concept of AUV positioning using an acoustical differential delay and Doppler tracking system [Ref. 2]. The proposed system involved a single low-cost omnidirectional hydrophone mounted on an AUV and a two part external dual frequency transmitting subsystem. This navigation system would provide a two dimensional grid position for an AUV. The envisioned system is based on tracking differential delay and Doppler information between the two external transmitters and the passive onboard hydrophone [Ref. 2].

Opderbecke and Durieu (1994) developed an algorithm for AUV localization using a combination of reference beacons and an internal dead reckoning system [Ref. 3]. The reference beacons were modeled with both known and unknown / estimated positions in order to simulate environmental conditions. A Kalman filter was used to refine position data and eliminate erroneous readings. This navigation data processing system was tested in simulations with an indoor mobile robot employing a laser range finder in place of an acoustical system, with promising results [Ref. 3].

Actual sea trials of an AUV navigation system were conducted by Scherbatjuk and Vaulin (1994) using an Integrated Positioning System (IPS) for the MT-88 underwater autonomous vehicle [Ref. 4]. The IPS combined an on-board inertial navigation system (BANS) with a long baseline acoustical system (APS). Two external acoustical transponders were used in conjunction with a transponder onboard the AUV. Favorable test results included an estimated AUV position error dispersion of 5.8 to 8.55 meters over a range in excess of a 1000 meters. These tests were conducted at a depth of 3100 meters of water which is considerably deeper than the near-surf zone which this present study is concerned with [Ref. 4].

Lurton and Millard (1994) studied the feasibility of a Very Long Baseline (VLB) acoustical positioning system for AUVs [Ref. 5]. Their focus was on deep ocean data gathering missions for AUVs which require long range systems (over distances of 50 to 100 km). The authors attempted to provide solutions to the many challenging problems facing deep ocean positioning systems. One of these problems is the phenomena of 'multipath' acoustical signals (bouncing off the ocean floor and ocean surface). Reflected multipath sound returns that are received by sound analysis equipment contain erroneous position data. Another source of problems for VLB acoustical navigation systems arises from the fact that the ocean contains many layers of variable salinity and temperature. The speed of sound through water is effected by salinity and temperature changes such that it is also variable through the layers of the ocean. Most common acoustical positioning software programs assume a preset speed for sound travel. Hence, a non-constant sound speed introduces another source of error in VLB acoustical systems. Finally, the VLB navigation system examined by Lurton and Millard (1994) is based on bottom-moored acoustical transponders. Moored objects are subject to ocean currents which move their

location with in an arc defined by the mooring cable. Therefore, bottom-moored sonar transponders do not have a fixed position and AUVs that employ these transponders for navigational purposes would have a large built-in positioning error which is unacceptably high. The authors conclude that an AUV mothership with an Ultra Short Baseline (UBS) navigation system may be a more economical alternative. The numerous problems presented in the study by Lurton and Millard (1994) may have only limited effect on an AUV in the near-surf zone, but the authors conclusions pointing towards an USB acoustical system are significant in that they give us a better idea of what employment schemes to use [Ref. 5].

Finally, Brokloff (1994) explored the possibility of using a sonar Doppler system to navigate AUVs [Ref. 6]. The Doppler system requires a known starting-point location to which velocity calculations are used to update current positions. The author's envisioned AUV is limited to within 1000 feet of the ocean floor which is well with in the very shallow water depths of the near-surf zone. Brokloff presented an algorithm for solving Doppler sonar equations which overcome many error sources associated with Doppler systems. However, position errors as a percentage of distance traveled by an AUV were 33% to 39%, which is considered unacceptable for mine-hunting AUV missions [Ref. 6].

C. THESIS SCOPE

Problems of current acoustic navigation systems include the inability to provide positional data to the vehicle, and the need to have a tether on the vehicle. The focus of this thesis is to examine an alternative acoustical navigation system to those discussed above for Autonomous Underwater Vehicles. The desired positioning system would be intended for an AUV with a mine-hunting mission in very shallow waters. A low cost, "off the shelf" commercially produced acoustical navigation system , called DiveTracker, is viewed as a potential solution and was purchased and installed in the NPS Phoenix II AUV for testing and evaluation. The DiveTracker Short Baseline (SBL) acoustical system contains two transponders attached to a fixed reference point and a third transponder installed on the AUV. This SBL system has been integrated to the NPS AUV onboard computer navigation system which has a differential GPS positioning system and is planned to have a small size INS system in the near future. The DiveTracker acoustical

navigation system was tested to determine it's characteristics, reliability, and accuracy of position data in a number of different real scenarios which would be found in a mine-hunting mission in very shallow waters.

D. THESIS STRUCTURE

This thesis is structured in the following manner; Chapter I is an introductory chapter with background information and thesis objective. Chapter II contains a description of the DiveTracker acoustical system and how it is integrated into the NPS Phoenix II AUV navigation system. Chapter III provides a description of experiments and the goals for those experiments. Chapter IV has test results from laboratory and field work as well as analysis of those experimental results. Conclusions and recommendations for further study and fleet deployment are provided in Chapter V. All figures are found in Appendix A with corresponding MATLAB data analysis programs in Appendix B.

II. DIVETRACKER SYSTEM

A. GENERAL DESCRIPTION

DiveTracker is a multi-functional underwater instrument capable of being a navigation, communication, and data computing system [Ref. 7: p.1-7]. It is produced commercially by Desert Star Systems in Moss Landing, California, and was originally designed as an aid to scuba divers. The basic DiveTracker DT1-D-S module is a hand held box about the size and weight of a brick which scuba divers carry with them underwater (see Figures 1 and 2). It is capable of monitoring the diver's air tank pressure, measuring the diver's depth under water, navigating on a relative grid coordinate system, and has limited underwater communication functions. DiveTracker navigation and communication functions are accomplished via sonar signals transmitted between a scuba diver with the basic DT1-D-S module and a mothership. The mothership, in this case, would have a DiveTracker surface station (known as a DT1-DRY model) connected to an acoustical Short Baseline (SBL) with two 40 kHz sonar transducers and an onboard personal computer (see Figures 3, 4, and 5). The DT1-D-S model carried by the diver has a small function key pad with an LCD display screen. A scuba diver can toggle through function menus on the DT1-D-S display using a magnetic wand on a built-in keypad. Software programs to run the various DiveTracker functions are included with the hardware when purchasing the DiveTracker system. These programs will be discussed in further detail later in this chapter.

Implementing the DiveTracker navigation system to Autonomous Underwater Vehicles has been accomplished by installing a stripped version of the diver DT1-D-S module, known as the DT1-MOD model, in an AUV. The DT1-MOD module does not have a LCD display screen or a keypad. It is mounted inside the AUV and interfaced with the AUV onboard execution level computer in order to provide current position information relative to the DiveTracker baseline. A 40 kHz sonar transponder is mounted on the outside of the AUV hull and connected to the DT1-MOD module in order to transmit sonar signals back and forth between the mothership and the AUV. Desert Star Systems advertise a 1000 foot maximum depth rating and a 3000 foot maximum range using this configuration [Ref. 7: p. 1-11].

B. NAVIGATION USING DIVETRACKER

As described above, the DiveTracker navigation system used in the Naval Post Graduate School Phoenix II Autonomous Underwater Vehicle employs a single sonar transponder mounted on top of the AUV hull and two transponders in a stationary acoustic Short Baseline (SBL). One of the key features of this system is its low cost, and the capability to provide navigational data to both the autonomous vehicle, and the user operated base station. For a mine-hunting mission the AUV is envisioned traveling through an uncharted mine field in the near-surf zone in order to locate mines. The SBL transponders could be mounted on the hull of a mothership which could safely stand off (up to one kilometer) from the dangerous mine field (see Figure 6). In a more clandestine operation, the baseline SBL transponders could be deployed by a SEAL team.

1. Distance Calculations

The DiveTracker navigation system is based on the triangulation of timed sonar signals. Assuming a know speed of sound through water, and a fixed baseline length between the two stationary transponders, the distances between the baseline units and the mobile transponder are easily calculated. Figure 7 displays the basic configuration of the three transponders, the sonar pinging sequence for the transponders, and the calculations which are required for determining distances between them. For this configuration, using single frequency pings, a repeating sequence of four sonar pings is needed for each set of distance calculations. The first ping travels from the stationary baseline transponder labeled station #1, to the mobile transponder on the AUV. The second sonar ping travels back from the mobile unit to station #1. At this point in the pinging sequence, the base station will know the distance from station #1 to the mobile unit which is called the r1 distance. This r1 distance is calculated by the base station by dividing the travel time required for the first two sonar signals in half and multiplying by the preset speed of sound through water. The third ping travels from station #1 to the mobile unit on the AUV. After the third ping, the AUV will also know it's distance from station #1 through a similar set of calculations of r1 distance using the second and third ping travel times.

The position from the mobile unit to the second pinger in the baseline is called the r2 distance. The baseline calculation of r2 position data is determined from the third and fourth sonar pings and the known r1 distance. The fourth ping in the sequence travels from the mobile unit to

station #2. At this time, the base station can calculate the travel time for the fourth sonar ping by subtracting the known r1 travel time from the total time between initiating ping #3 and receiving ping #4. After simple multiplication by the speed of sound through water, the sonar ping #4 travel time is converted into the r2 distance.

R2 position data is determined by the AUV from the fourth sonar ping (the final ping of the sequence) and the first ping from the next sequence. The fourth ping in the sequence travels from the mobile unit to station #2. At this time, the base station initiates the next sequence of sonar pings by sending out a new ping #1 from station #1 to the AUV. The mobile unit can calculate the travel time for ping #4 by subtracting the known r1 travel time from the total time between initiating ping #4 and receiving the new ping #1. The AUV then performs the multiplication of the ping #4 travel time by the speed of sound through water to find the r2 distance.

For navigational purposes, the distances labeled r1 and r2 in Figure 7 are entered by the DT1-DRY module into the AUV on board computers. The AUV computers translates these two distances into an X-Y position on a two dimensional grid system fixed with respect to the stationary baseline. Further details of the AUV navigation system are discussed later in this chapter. This method of positioning the AUV assumes a known position for the baseline. Determining short baseline position can be done through any means available to the basestation; in a mine-hunting scenario in which the baseline is fixed to a mothership's hull, the position of the basestation is most likely accomplished through a GPS navigation system inherent to that naval vessel.

2. DiveTracker System Software

In order to compute the distance calculations outlined above, Desert Star Systems provides software programs which control the operation of various DiveTracker system hardware. All DiveTracker software comes on standard, MS-DOS formatted, 3.5" disks and is included in the purchase cost of the DiveTracker system. The operating programs which control the hardware must be installed into the memory storage that is built into the DT1-MOD and DT1-DRY modules prior to using the DiveTracker system.

DiveTerm is the name of the utility program which allows an IBM compatible personal

computer to communicate with DiveTracker hardware through a serial link. DiveTerm is used to install and run the operating programs which control DiveTracker hardware. The DiveTerm program is also used to initially configure the DiveTracker operating programs so that preset information, such as the baseline length or the number of AUVs operating during the mission, are known [Ref. 7: p. 2-3].

Configuration files for presetting assumed information are vital for running DiveTracker operating programs. A copy of a typical configuration file is located in Appendix B. The configuration files are written by Desert Star Systems and are extensive but also very user friendly. The baseline operator or AUV pre-mission programmer simply edits the configuration file and adjusts system parameters for the current AUV mission. This must be done for the operating programs stored in both the DT1-MOD and DT1-DRY modules prior to using the DiveTracker system. Preset initialization information in a DiveTracker configuration file includes data exchange parameters, station function, station identification, baseline length, network type and protocol, number of divers, and surface station transducer depth. Some of these sections of the configuration file are self-explanatory but others are more complicated. The data exchange parameters include a choice of sonar receiving gain and transmitting power as well as signal pulse length. Station function and identification tells each of the DiveTracker equipment whether it is a surface station or an AUV. Network type and protocol is the preformatted data exchange sequencing required for timing sonar pings between DiveTracker units. Since more than one AUV or scuba diver can use the DiveTracker system simultaneously, this information must also be preset in the configuration file under the 'number of divers' section.

SmartDive is the primary operating program which controls DiveTracker hardware for AUV missions. SmartDive must be installed in the built-in memory of both the DT1-MOD and DT1-DRY and configured prior to using the DiveTracker system. This program performs the operational control within both the mobile unit (the DT1-MOD module) and the base station (the DT1-DRY module). The SmartDive program contains the sonar pinging sequence necessary to perform AUV distance calculations. SmartDive automatically removes the vertical component of distance between stations therefore allowing the r1 and r2 distances calculated in Figure 7 to be used on a two-dimensional positioning grid within the AUV navigation system. SmartDive and

other DiveTracker operating programs are often referred to as DiveCodes by the manufacturer [Ref. 7: p. 1-2 and p. 1-9].

DiveBase is the program which runs on a personal computer located on the basestation mothership and connected to the DT1-DRY module. The DiveBase software is designed to acquire, store, and display mission data from the DiveTracker equipment installed on an AUV and the basestation. DiveBase has two operating modes; real time and replay. In the real time mode, DiveBase displays a picture similar to a radar-screen. This visual display graphically tracks AUVs with depth and position information relative to the baseline. A person operating DiveBase can send and receive pre-formatted messages to and from the mobile unit as part of the DiveTracker communication function. This preformatted communications function has not yet been utilized for NPS AUV missions but will be activated in the near future with the thesis work of LCDR. Kevin Reilly. In addition, DiveBase will automatically warn a basestation operator if the AUV violates preset mission profiles (such as maximum allowable AUV depth) and records all mission data on computer floppy disk. In replay mode, DiveBase will review mission data using the same radar screen visual display in chronological order [Ref. 7: p. 1-4].

C. DIVETRACKER / AUV INTEGRATION

Importing the DiveTracker position data into the AUV navigation system is accomplished by the DiveTracker DT1-MOD module through a serial link to the AUV computer system. The r1 and r2 distance data is sent to an AUV computer where it is converted to a relative grid coordinate position by the AUV navigation system. The DT1-MOD module is physically located inside the AUV in the center compartment next to the AUV computers (see Figure 8). As mentioned above, a serial link connects the DT1-MOD module to the AUV computer system. The sonar transponder used by the DiveTracker navigation system is physically located on the topside of the AUV hull and has a cable connection to the DT1-MOD module inside the AUV (see Figures 8 and 9). An external serial port on the AUV is provided for data link connection between an external PC and the DT1-MOD module for preprogramming and reconfiguration of existing operating programs. During mine-hunting missions this external port would not be used and is plugged with a waterproof cap. Control of the NPS AUV becomes totally autonomous during

normal operations and is based on pre-mission planning and program code generation.

1. AUV Control System

The navigation system is only one component of an extensive control system in the NPS Phoenix AUV. The Phoenix AUV contains four cross body thrusters, two propulsion screws, and eight adjustable fins for maneuvering control (see Figures 8 and 9). The NPS AUV also has two additional sonars for object detection and classification [Ref. 8]. On board computers control these maneuvering and sonar systems in order to make the Phoenix II AUV autonomous. The AUV computer system is based on a tri-level software control architecture comprising of strategic, tactical, and execution levels (see Figure 10), [Ref. 8].

The Strategic software level is a rule-based mission controller run on a Sun Voyager notebook workstation in the AUV using 'Prolog' computer code. The strategic level programming cycles through Prolog predicate rules to manage the discrete event logical aspects of mission related decisions [Ref. 8]. The strategic level programming is likened to the commanding officer of a submarine who decides the over all policy for AUV mission operation. Commands to actually operate vehicle equipment are performed separately, at lower levels in the software architecture, but the overall mission objectives and condition states are held and monitored at the strategic level. Hence, the strategic level of software maintains the "big picture"; it is at this level that basic mission parameters are set such as the general course of AUV travel, waypoints, object avoidance and error recovery procedures.

The execution level is the software program written in 'C' computer code which actually controls the subsystems in the AUV. The execution level activates responses in AUV equipment as dictated by the commands from higher level software. The execution level software is seen as the watchstander on a ship or submarine who actually has the hands-on control of the vehicle equipment, such as a helmsman for example. Execution level programs in the AUV are found within the GESPAC computer. The GESPAC computer uses a Motorola 68030 central processing unit (CPU) and card cage connections for analog / digital (A/D) signal interface [Ref. 9: p.10 - 11].

The tactical level is written in 'C' computer code and is used as an interface between the strategic and execution levels. The tactical level is queried by the 'Prolog' predicates in the

strategic level and returns a true/false response to questions concerning the state of the AUV. The tactical level also interacts with the execution level by sending commands for vehicle performance requirements to the execution level and by requesting data for evaluation of AUV condition states. The tactical level is likened to the Officer of the Deck (OOD) on a naval vessel who carries out the mission orders from the commanding officer by giving the required maneuvering commands to his helm and leehelm watchstanders. The tactical level interfaces at real time with the execution level by asynchronous communications in the Sun computer. Execution level sonar, DiveTracker, and sensor data are updated to the tactical level at a 10 Hz rate [Ref. 9: p. 11].

2. AUV Navigator

The NPS AUV navigator software is one of the tactical level programs used to control the AUV. The tactical level software is comprised of three major components; the OOD, the navigator, and the sonar officer. These three tactical software members control the overall performance of the major equipment systems on board the AUV. The navigator program uses a combination of inputs from GPS, dead reckoning, and DiveTracker navigation systems to determine it's position on a two dimensional grid. This position data is then fed to the OOD, as required by the OOD, for further evaluation and computation of new orders.

The NPS AUV navigator system processes position data by starting with a known initial position. It then uses a water speed sensor and gyro heading information to dead reckon a new position at a 6 Hz rate. The navigator also receives incoming position data from DiveTracker and GPS systems. The navigator compares it's own calculated current position from on board dead reckoning to the external sources. Since GPS is rarely available during underwater AUV missions, DiveTracker positioning is taken as the most accurate system and has precedence over all other inputs. The navigator uses a Kalman filter to process data inputs from all navigation sources. Therefore, the navigator automatically adjusts it's location to that of the DiveTracker position on a 6 Hz rate unless erroneous information is detected and thrown out by the filtering process.

III. EXPERIMENTAL PROCEDURES AND GOALS

A. GOALS AND OBJECTIVES

The purpose of this study, as stated in Chapter I, was to investigate the performance of an acoustical navigation system that could be used by an Autonomous Underwater Vehicle, whose mission it was to search, locate, and map the position of sea mines in the near-surf zone. In order to accomplish this task, the DiveTracker acoustical short baseline navigation system was incorporated into the Naval Postgraduate School Phoenix II AUV. Extensive testing was conducted to investigate the DiveTracker positioning system accuracy and precision for mine-hunting AUV missions, with the goal to gage DiveTracker performance against preconceived notions of mandatory mine-counter measures accuracy.

For an AUV to proceed through a mine field and formulate a map of mine positions, precise navigation is required. The position data will also be used for reacquisition and disposal of the mines. Thus, when operating at the close ranges that are required to identify and dispose of such ordnance, extreme mapping accuracy is necessary to avoid unwanted detonations. Therefore, a distance of a meter was chosen as the desired accuracy for AUV navigation. This numerical figure was also based on the current limitations of the military versions of GPS. As mentioned earlier, GPS unfortunately does not work under water [Ref. 10]. Although, since GPS is the most accurate navigation system to date, it was used as a yard stick for gaging the worthiness of underwater acoustical positioning systems.

B. TEST TANK EXPERIMENTS

Initial testing of the DiveTracker navigation system took place in the NPS AUV test tank located in Monterey, Ca. This test tank is a twenty foot long by twenty foot wide, square-shaped pool with a water depth of about ten feet (Figure 11). A grid pattern, with lines spaced 30 inches apart, is painted on the interior walls and the bottom of the tank to aid in positioning the AUV for experiments [Ref. 9: p. 16]. The acoustical short baseline with the DTI-DRY module and two transponders were placed on one side of the test tank. The baseline sonar transponders were submerged approximately six inches below the water surface. A personal computer with the

DiveBase program installed in it was connected to the DTI-DRY module. After integrating the DT1-MOD module into the Phoenix II AUV, with a sonar transponder attached to the top of the hull, the AUV was placed in the test tank. In this equipment configuration, position data was monitored visually in the real time mode display of the DiveBase program.

Initial experiments in the test tank began with static tests in which the AUV was positioned at a fixed known location, such as the center of the pool, to see if the DiveTracker system could find the AUV and produce an accurate position. Other experiments included transits from one known location to another, along a prescribed track within the test tank. These trials were conducted in order to determine how well the DiveTracker system could track a moving AUV, as opposed to the determination of position of a fixed point.

Unfortunately, experimental results from this equipment set-up were inconclusive. While the DiveTracker acoustical system was sending and receiving sonar signals between the mobile and fixed transponders of the short baseline, the resulting position data on the DiveBase computer screen was confusing at best. The grid position of the static AUV in the test tank would appear to jump randomly on the DiveBase visual display. Occasionally, the correct positional fix would appear on the baseline computer display but it would last only a few seconds prior to jumping elsewhere. Dynamic trials created even more chaotic test results; prior to a transit with in the pool, the DiveTracker system might occasionally fix the AUV position accurately. But once the AUV started moving, the DiveBase display gave impossible grid locations which were outside of the physical constraints of the tank!

Further test tank experiments, including the development of execution level software, involved placing the Phoenix II AUV on a bench located next to the pool. An extension cable was installed at the sonar hull connection where the mobile DiveTracker transponder is mounted to the AUV. In this manner the DiveTracker sonar transponder was connected, through the extension cable, to the DT1-MOD module with in the AUV, but was free to be placed anywhere in the pool desired. At the same time, this configuration allowed for the AUV to remain out of the water, making it possible for the DT1-MOD module to be connected through the AUV's external serial port to a lap-top personal computer. This additional personal computer was used to monitor and record the raw r1 and r2 numerical data as seen by the AUV navigation system.

Various changes were made to the adjustable parameter values found in the configuration file for running the SmartDive operating program. Because it was suspected that tank reverberations interfered with echo receiving, sonar signal power was dropped to minimum strength as well as the receiver gains. This was done in the hope of finding the best operating parameters for dealing with highly distorted echo pulse shapes. Although the DiveBase position data was considerably more stable at low power settings, the r1 and r2 numerical results were still not reliably repeatable. The conclusion was reached that the reverberations of sonar signals off the NPS test tank walls were flooding the system with false signals. As in the case of deep ocean acoustical survey systems, the DiveTracker positioning system was processing reflected multipath sound returns. In this case the reflected erroneous signals were produced, not by the ocean floor, but by the test tank walls and bottom. To correct this problem would involve covering the test tank walls with an absorbent coating (an expensive solution) or moving to another test site.

C. SALT WATER EXPERIMENTS

After the disappointing, but somewhat expected trial results from experiments conducted at the NPS test tank, further experiments were moved to the Monterey Bay Aquarium Research Institute (MBARI) facility located at Moss Landing Harbor (see Figure 12). The MBARI facilities include a docking pier area which provided a salt water environment for testing the DiveTracker navigation system. The acoustical short baseline connected to the DTI-DRY module was placed at one end of the pier with the two fixed sonar transponders submerged just below the surface of the water. As in the test tank experiments, a personal computer with the DiveBase program installed in it was connected to the DTI-DRY module. This personal computer was used to visually monitor the DiveBase program's radar-like display in real time mode. Entering the salt water environment required adjustments to the configuration files which ran the operating programs with in the DiveTracker hardware. Sonar signal strength, maximum tracking range, and receiver gains were all boosted to allow for the larger size of the pier facility. In addition, the baseline length was expanded from the 20 foot limitation of the test tank wall, to a new length of 40 feet.

Initial pier experiments employed the scuba diver version of the DiveTracker mobile unit

system, referred to previously as the DT1-D-S module. In these pier tests, and because the AUV was not ready for salt water trials, which has the DT1-MOD module installed, the DT1-D-S module replaced the AUV. The DT1-D-S module acted as a mobile DiveTracker unit and was connected to the same sonar transponder that was taken off the AUV. The identical SmartDive operating program which ran the DT1-MOD module in the AUV, also ran the DT1-D-S module used in these experiments. A laptop personal computer was plugged into the DT1-D-S module to access the r1 and r2 data as seen by the mobile unit. These r1 and r2 distances from the DT1-D-S module would be the same as those fed to the AUV navigation system by the DT1-MOD module.

1. Static Tests in Salt Water

The MBARI facility provides an excellent saltwater test environment and experiments were conducted starting with static trials in which the DT1-D-S module was positioned at a fixed known location, such as a pier opposite of the one where the basline was set up. The mobile unit was dipped in the water at the same depth as the baseline sonar transponders. Distances between the mobile unit and the baseline were carefully gaged with a metal tape measure to see if the DiveTracker system could produce an accurate position. Initial static tests also included "zero length trials" in which the mobile unit was placed directly next to one of the baseline transponders. The purpose of these particular tests was to calculate an offset distance which the DiveTracker system automatically produces in the r and r2 calculations. If such an offset existed, further static tests in which DiveTracker measurements were compared to tape measured distances would have to account for this added offset distance.

Longer range static tests, "beyond the tape measure", were conducted across the width of the Moss Landing harbor channel on opposing piers, using the same equipment set-up described above. These longer range tests could not tell us the precision of the DiveTracker system position data compared to a known measured distance but they still had value. Such experiments, conducted at approximately 200 and 250 feet from the baseline, gave us an indication of DiveTracker performance reliability outside of the previous physical limitations imposed by the MBARI docking pier area.

2. Dynamic Tests in Salt Water

Dynamic experiments performed in the harbor were also initially conducted using the

DT1-D-S module with the serial-linked laptop computer recording r1 and r2 distances. DiveTracker mobile unit transits used a row boat and were carried out with the DT1-D-S module and transponder fixed to the stern of the boat. As before, the mobile sonar transponder was placed at the same depth in the water as the baseline transponders. Use of a row boat meant the mobile unit's path of travel did not follow a prescribed track that could be controlled, such as those dynamic experiments carried out in the NPS tank. However, pier dynamic trials were conducted over considerably longer distances than those found in a pool and so were worth considerably more research value. Dynamic experiments provided insight into determining how well the DiveTracker system could track the position of a moving AUV.

Dynamic tests in the salt water environment were also done at longer ranges, beyond known starting and stopping positions, in order to "push the envelope" of the DiveTracker system performance. Transits were conducted both perpendicular and parallel to the baseline to measure any difference in tracking ability of the positioning system. Additionally, investigations were done at various oblique angles from the baseline in order to define the "window" in which the DiveTracker "looked outward". This particular set of studies attempted to define any "blind spots" in which DiveTracker coverage was incomplete. During these experiments, transient speeds were limited to the rowing power of individuals performing the trials plus the effect of the currents in the Moss landing Harbor. However, since the NPS AUV has a cruising speed of approximately two knots, the slow row boat pace was suitable for such endeavors.

3. Testing the Effects of Variable Configuration File Values in Salt Water

Further experiments conducted at the MBARI Moss Landing pier facility entailed tests in which the configuration file adjustable values were varied to determine any distinguishable difference in DiveTracker system accuracy. The mobile DiveTracker unit containing the DT1-D-S module, lap-top computer, and transponder was placed in different static positions. These positions had been tape-measured from both of the fixed short baseline sonar units so the distances were known. The baseline length was varied from 20 to 38 feet while all other variables were held constant. As the configuration file variable for baseline length was adjusted, the physical baseline length was also moved to match the distance in the configuration file. Since triangulation calculations are more accurate when using longer baselines, these tests were conducted in order to

determine if such a difference in accuracy would be noticeable in the MBARI pier test area.

Another set of static tests, which included changing a configuration file adjustable value, involved experiments to examine the effect of variable sonar pulse length. In a nut shell; the shorter the duration of time to transmit a sonar pulse means the shorter the minimum range of detection. Since the length of the sonar pulse signal effects the minimum range detectable by an acoustical positioning system, several "zero length trials" were conducted. The DiveTracker mobile unit was placed in a known position near one of the baseline transponders. Pulse length was adjusted from 4000 to 1000 milliseconds in increments of 500 milliseconds while all other variables were held constant. Results were examined to find any effect on the offset distance placed on r1 and r2 positions by the DiveTracker system.

Finally, the DiveTracker owner's manual, published by Desert Star Systems, states that the vertical component of the DT1-D-S module's distance from the baseline is automatically removed from the r1 and r2 calculations by the SmartDive program. To verify that the depth of an AUV would not effect position data given by the DiveTracker system, static tests were conducted at known positions with in the MBARI docking pier area. The mobile unit was initially placed at the same depth as the baseline transponders, which was very close to the water surface. While all other variables were held constant, the depth of the DT1-D-S module's sonar transponder was then adjusted from a near-zero depth to the bottom of the Moss Harbor.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

A. STATIC EXPERIMENTS

Static experiments were primarily conducted to determine the accuracy of the DiveTracker positioning system. As the testing name suggests, the DiveTracker DT1-D-S module was placed in a stationary location and the r1 and r2 distances were recorded on a lap-top personal computer connected to the mobile unit. Instantaneous analysis of the DiveTracker positioning system was performed by observing the DiveBase real-time visual display; the known DT1-D-S module's physical location was matched against where the DiveBase marked the mobile unit's position relative to the baseline. Most of these experiments were completed over prescribed distances, so as to compare the DiveTracker ranges to that of tape-measured intervals. Numerical analysis was then done to not only correlate these distances for the purposes of determining the level of system accuracy, but also to measure the standard deviation and distribution of positional data points. It was hoped to find that the DiveTracker-generated-distances would have a small standard deviation over the duration of an experiment with a Gaussian distribution of data plots around the mean calculated distance. This would provide further evidence of the system's precision and reliability by showing that the data for static tests was clustered in a very dense normal distribution.

1. Short Range Static Tests

Figure 13 displays the equipment configuration for test #155, conducted at the Monterey Bay Aquarium Research Institute (MBARI) pier facility in the Moss Landing Basin. The acoustical short baseline was placed on the south pier with a 39 and 1/2 foot (12.04 meters) separation between baseline sonar transponders, which are labeled stations #1 and #2. The mobile unit, labeled MU in Figure 13, was placed 25 feet (7.62 meters) away from the baseline with measured r1 and r2 distances of 22.667 and 45.541 feet (6.909 and 13.881 meters) respectively. Figures 14 and 15 are graphs showing the data points -vs- DiveTracker-generated-distances, as collected by the DT1-D-S module. These figures were produced using a MATLAB m-file program called "matmoss.m", a copy of which is found in Appendix B. In these graphic presentations of the mobile unit position , the r1 or r2 distance for each data point appears as a

circle. The circles from numerous positions logged over time are connected by a line in order to track the sequence of recorded distances. The chronological order of the data points is from left to right on the graph, and therefore a static test should appear as a straight line. In fact, the connecting lines in Figures 14 and 15 are nearly straight and the DiveTracker r1 and r2 distances are close to the measured values. The r1 distance is off by 2.44 inches (0.062 meters) and the r2 distance is off by 5.20 inches (0.132 meters).

Figure 16 displays the equipment layout for two more static tests; #98 and #99. In these experiments, the baseline was placed on the west pier with a 25 foot (7.62 meter) separation between baseline sonar transponders. The mobile unit was placed 90 feet (28.5 meters) away from the baseline with measured r1 and r2 distances of 93.75 and 93.92 feet (28.575 and 28.626 meters) respectively. Figures 17 and 18 are the graphs showing the r1 and r2 position data for test # 98, as collected by the DT1-D-S module. Figures 19 and 20 are graphs showing the data points recorded during test #99. In both experiments, the DiveTracker-calculated-distances are very nearly the same as the tape-measured lengths. The r1 positions for both tests are off by less than 4 inches (0.1 meter). The r2 distances are off by 8.66 and 7.32 inches (0.220 and 0.186 meters) for tests #98 and #99 respectively.

These promising results point to an accuracy for DiveTracker-calculated-distances that is within inches (centimeters) of measured lengths. The positions are off by less than one percent of the total range measured. The DiveTracker-generated-distances were also verified by observing the DiveBase real time visual display. On the screen of the personal computer connected to the basestation module, the mobile unit icon was seen on the radar-like monitor produced by the DiveBase program to correctly simulate the actual position of the DT1-D-S module. Examining the standard deviation of data points for these static tests revealed the distribution of DiveTracker positions over time were very close to one another. For example, in test #98, the standard deviation for r1 data was equal to 3.425 inches (0.087 meters). Other values for standard deviation of DiveTracker data points are found on the r1 and r2 distance graphs in Appendix A. In all but one case, the standard deviation of the DiveTracker calculated distances was less than one percent of the total range. In the one exception, that of test #155, the r1 standard deviation was less than two percent of the total range.

Figures 21 and 22 show histograms for the measurements collected from the DT1-D-S module during test #155. These graphs reveal the distribution of data points surround the DiveTracker-calculated mean value and appear as a bell shape. The Gaussian overlay placed on top of the histogram confirms the normal distribution of position data coming from the DiveTracker equipment. These figures were produced using a MATLAB m-file program, called "mosshis.m", a copy of which is found in Appendix B. Histograms were also produced for tests #98 and #99, and can be seen in Figures 23 through 26. In all of the static tests discussed above, the histograms contain Gaussian-like distributions about the mean distance calculated by the DiveTracker equipment. Hence, at short ranges of 100 feet (30.48 meters) or less, the DiveTracker positioning system was found to be extremely precise, with normally distributed deviations.

2. Longer Range Static Tests

Although longer range tests could not be verified against known, tape-measured distances, they did provide important information concerning DiveTracker performance. Figure 27 displays the equipment configuration for test #86, conducted at the MBARI pier facility in the Moss Landing Basin. The basestation was placed on the south pier with a 40 foot (12.192 meters) separation between baseline sonar transponders, which are labeled stations #1 and #2. The mobile unit, labeled MU in Figure 27, was placed in a row boat which was tied to another pier in a position approximately 90 yards (80 meters) away from the baseline. Figures 28 and 29 are graphs showing the data points -vs- DiveTracker-generated-distances, as collected by the DT1-D-S module. These graphs display the typical straight lines that represent the distance to a fixed sonar transponder. Examining the histograms generated from this data (Figures 30 and 31) reveals the expected bell-shaped distribution of points about the mean calculated value.

Test #102 was another experiment conducted outside the tape-measured range. As Figure 32 demonstrates, the DiveTracker baseline was placed on the west pier at the MBARI facility. The mobile sonar transponder was taken via row boat across the Moss Landing Harbor Channel. The DT1-D-S module, with sonar and personal computer attached, were positioned in a fixed location, tied to a pier approximately 90 yards (80 meters) from the baseline. This static test provided confusing results upon first examining the graphs found in Figures 33 and 34. Although

the r1 range in Figure 33 appears to be accurate, the r2 data points in Figure 34 jump completely off the analysis graph normally used for these experiments. Figure 35 provides another look at the r2 distances from test #102 with re-scaled axes. It can be seen in this figure that the DiveTracker system has found the mobile transponder in two possible locations; one near 90 yards (83 meters) and the other at about 4,050 yards (3,700 meters). The DiveBase real time display also showed these two possible positions on the basestation monitor. Obviously, the former position is the correct one of the two lengths provided by the DiveTracker system. This loss in accuracy was attributed to an obstructed sonar signal path between the baseline and the mobile unit. The east pier support pilings partially masked the base station #2 transponder from a direct path to the mobile unit. With the base station transponder blocked from sending a direct path sonar signal, the DiveTracker system produced the erroneous r2 data seen in Figures 34 and 35.

Histograms from this particular experiment are particularly interesting and useful in test analysis because of the pier masking problem described above. Although Figure 36 shows a general bell-shaped graph, there is a very large spike around the DiveTracker r1 mean value. This spike in the data is a very promising result, because it demonstrates the DiveTracker system's ability to pin point the measurement of a fixed location at longer ranges. However, the Figure 37 histogram reveals the DiveTracker system flaw; a characteristic twin-position-response caused by the partially masked base station transponder. The actual distance and an incorrect distance calculated from bogus sonar signal returns were created. Two large spikes on the histogram found in Figure 37, at two completely separate distances, provide an idea of the DiveTracker system's limitations and response behavior when a direct path between transponders is not available.

After encountering the pier masking problem found in test #102, experiments at longer ranges were carried out with the baseline established on the MBARI east pier, so to avoid this dilemma. During test #122, as seen in Figure 38, the mobile unit was once again placed across the Moss Landing Harbor Channel, fixed to the opposing pier. There was an approximately 70 yard (65 meters) separation between the baseline and the mobile unit for this experiment. Figures 39 and 40 contain the r1 and r2 positional data from test #122. These graphs prove that the DiveTracker system acquired and maintained the location of the fixed mobile unit without producing the erroneous distances found in test #102. And similar to the measured short range

static tests, the standard deviation of data points was found to be less than one percent of the total distance measured. In fact, the standard deviation was less than one half of one percent of the r1 and r2 ranges measured in both tests #86 and #122.

Watching the DiveBase visual output also verified the accurate tracking of the fixed DT1-D-S module at longer ranges. The mobile unit was correctly positioned on the basestation monitor screen with respect to the baseline transponders' relative positions and distances. Observing the histograms from test #122 (Figures 41 and 42) once again reveals the familiar bell-shaped output from a normally distributed set of data points. The Gaussian distribution is centered around the mean value calculated by the DiveTracker positioning system. From this analysis, it is safe to conclude that DiveTracker performance does not diminish at longer ranges, as long as a direct path for sonar pulses is available.

3. Zero Length Trials

With DiveTracker accuracy well established between 8 and 90 yards (7.3 and 82.2 meters), a brief look at minimum range testing is necessary. Zero length tests were conducted for two purposes; to find a minimum detection range (if such a distance existed) and to examine the effect of the " distance measurement offset compensation" value on position accuracy. This offset compensation distance is found in the DiveTracker configuration file, which contains the preset values for DiveTracker operating codes. The DiveCode (SmartDive was the operating code used in all experiments) controls the operation of the sonar transponders and subtracts the measurement offset compensation value from the calculations for r1 and r2 distances. A thirty-six inch (0.9144 meter) offset compensation is preset in the configuration file by Desert Star Systems to account for the electronic delays in processing timed sonar signals. Since the previous short range tests provided precision to within inches (centimeters) over measured distances, a negligible adverse effect on position calculations was expected but the minimum detection range was unknown.

Zero length experimental procedures were accomplished by placing the DT1-D-S module adjacent to one of the base station transponders. Figures 43 and 44 are the results of tests # 150 and #151 in which the mobile DiveTracker unit was positioned next to station #1. The DiveTracker output produced nearly straight lines on the data graphs, which is typical of figures

representing fixed transponder positions. The mean DiveTracker distance calculated for test #150 was 5.71 inches (0.145 meters) and the mean distance calculated for test #151 was 5.16 inches (0.131 meters). Figures 45 and 46 are the results of tests # 152 and #153 in which the mobile DiveTracker unit was positioned next to station #2. Once again the steady, straight line connecting a static position distance over time is apparent in these figures. The mean DiveTracker distance calculated for test #152 was 20.79 inches (0.528 meters). The mean DiveTracker distance calculated for test #153 was 18.70 inches (0.475 meters).

In all of the experiments, a known zero length was measured by the DiveTracker system to be equal to a distance between five and twenty inches (one and six centimeters). Because the" distance measurement offset compensation" value is subtracted from the range calculations, a negative position value would had been expected from the system if there was an adverse effect from the offset value. However, the mean DiveTracker-calculated distances did not have negative values, and so these results point to the preprogrammed offset compensation having no detrimental effect on measuring zero length distances. This conclusion is backed by the DiveBase visual display which placed the mobile unit icon on top of the nearest basestation transponder during all of the zero length trials. In addition, because the small error in r1 and r2 positional data was the similar to those experiments conducted at greater measured distances, it was also concluded that the DiveTracker system did not have a minimum detection range.

Re-examining the results from the zero length trials also provides another unexpected insight into the DiveTracker system performance. A comparison was completed of the standard deviations from tests conducted close to basestation transponder #1 and those conducted close to station #2. It was found that the standard deviation of r2 distances was three times as large as the standard deviation values from r1 data. Referring back to the other static tests performed earlier at greater ranges also points towards the same phenomena. In those previous experiments (such as tests # 155, #98, #99, #86, and #122), the r2 standard deviation was consistently found to be approximately twice as large as those from r1 distances. This difference in the data position density about a mean DiveTracker-calculated value can be explained from scrutinizing the pinger sequence and distance calculations outlined in Figure 7. The r1 distance calculations involve the travel times between basestation #1 and the mobile unit. But the r2 distance calculations involve

the travel times for pings between both basestations and the mobile unit. Ergo, r2 data is dependent on twice the amount of travel times required in finding a distance as the r1 calculations. Consequently, r2 data is subject to twice the amount of errors associated with precision distance calculations. The DiveTracker r2 distances are concluded to be less accurate than those of r1 data and the standard deviations for r2 distances are frequently twice the r1 data standard deviation values.

B. DYNAMIC EXPERIMENTS

Dynamic experiments were conducted primarily for the purpose of examining the DiveTracker system's ability to track a moving AUV. The DiveTracker mobile unit was placed in a row boat and moved along a prescribed test path with the sonar transponder dipped in the water. The r1 and r2 distances were recorded on a lap-top personal computer connected to the DT1-D-S module inside the row boat. Most of these experiments were completed within the MBARI pier facility where the mobile unit's track was fairly well known. It was therefore possible to judge distance data with some certainty, although not with the precision of tape-measured intervals. Numerical analysis was done to discover how well the DiveTracker system tracked the moving boat and also to define the standard deviation of positional data points when the low frequency portion of the distance information was eliminated. It was hoped to find that during dynamic experiments, the high frequency portion of DiveTracker-generated-distances would have the same dense distribution of positional data points as those found in static tests.

1. Short Range Dynamic Tests

Figure 47 displays the equipment configuration for test #87, conducted at the MBARI pier facility in the Moss Landing Basin. The acoustical short baseline was placed on the south pier with a 39 and 1/2 foot (12.04 meters) separation between baseline sonar transponders. The mobile unit was placed in the row boat and taken along a path which was perpendicular to the baseline. The starting point of this dynamic test was the same location as that of test #86 (a static test described earlier) and the experiment ended at a location near the baseline. Figures 48 and 49 are graphs showing the data points -vs- DiveTracker-generated-distances, as calculated by the DT1-D-S module. As described before, the graph depicts the r1 or r2 distance for each data point as a

circle. The circles from numerous positions logged over time, are connected with a line which tracks the sequence of recorded distances. The chronological order of the data points is from left to right on the graph, and therefore a dynamic test should appear as an arc or sloped line depending on the path of the row boat.

In the case of test #87, where the row boat was moving inward towards the baseline, the curves for r1 and r2 distances over the duration of the experiment should appear as a negative-sloped line. The path lines in Figures 48 and 49 do contain the generally downward sloping line but with occasional spikes that are attributed to sudden speed changes on the part of the row boat operator. During this dynamic experiment, the DiveTracker mobile transponder was dangling in the water and was observed to tip sideways when subjected to sudden changes in speed. Thus, two important discoveries were made in the process of conducting test #87; not only did the DiveTracker system follow the movements of the transient DT1-D-S module, as seen by the r1 and r2 distance graphs (Figures 48 and 49) and on the DiveBase visual display, but the accuracy of the system was effected by the angle of the mobile transponder. When the DT1-D-S module transponder was kept at an angle in plane with the basestation sonar heads, the system continued to work well. But if the transponder was accidentally tipped, precision was lost. This conclusion further justifies earlier static test results in which system accuracy was temporarily lost due to obstructions between the baseline and the mobile DiveTracker transponders.

The perpendicular path, dynamic experiment was reconstructed again during test # 91 (see Figure 50 for equipment configuration during this experiment). This time however, the DT1-D-S module transponder was attached to a fixed mounting under the row boat, similar to the sonar mounting found on the NPS AUV, in order to prevent a loss in tracking from a skewed sonar head. Figures 51 and 52 contain the r1 and r2 distance records from test #91. Once again the downward sloped path of an inward bound moving target is apparent. But in this trial, the r1 and r2 graphs are considerably smoother, thus supporting the fixed-sonar- mounting solution to the previous data-spike problem from test # 87.

Having successfully tracked the DiveTracker mobile unit on a path perpendicular to the baseline, the next set of dynamic experiments involved parallel tracks. As seen in Figure 50, the acoustical short baseline was established on the MBARI west pier for tests #92 and #94. The r1

and r2 data graphs for test #92 (see Figures 53 and 54) have a positively sloped arc which faithfully traces the outward bound, parallel path of the row boat as it passed by the baseline. The advancement of the row boat was also watched on the DiveBase screen display during these dynamic tests and found to match the real movements of the boat in the water. The position data graphs for test #94 (see Figures 55 and 56) have a negatively sloped arc which reliably follows the inward bound, parallel path of the row boat as it travels past the baseline.

Numerical analysis was performed on dynamic experimental results by eliminating the low frequency information (the change in distance attributed to transient movement) from the test data records. Studies were conducted on the high frequency information remaining from the dynamic experiments to compare the standard deviations of dynamic trail data points to analysis results from static tests. The high frequency standard deviations were divided by the mean values for DiveTracker distances calculated over the duration of each dynamic test. In this manner, a correlation between data point distribution values with respect to over all range for dynamic experiments could be matched against those taken from static trials.

A two-part series of MATLAB m-files were used to remove the low frequency portion of the data from dynamic test files for data analysis (see Appendix B). The experimental results are normally stored in a "two by n" size matrix for each trial run. The two column vectors in each test file contain the r1 and r2 distances recorded. A MATLAB program called "addtimemod.m" was used to place a time vector in the recorded files. A Kalman filter program called "highfilter.m" was then used to generate a smoothed track which was overlaid on top of dynamic test transits. The difference between the two tracks, called the error, is equal to the high frequency information. The same "highfilter.m" program, which scrubbed the low frequency information away from the raw data, also calculated a high frequency standard deviation value, and plotted the resulting information.

Figures 57 through 62 contain the plots of filtered data from dynamic tests #91, #92, and #94. Numerical analysis on test #87 was omitted because of the fore-mentioned sonar- mounting problem. The typical graph of high frequency information from a dynamic experiment appears as a jagged line with a generally horizontal path across the page. The x-axis contains the chronologically-ordered data points taken from the dynamic tests. The y-axis represents the high-

pass filtered DiveTracker ranges taken over the duration of the experiment. Comparing the standard deviations of the high frequency information reveals that dynamic tests have nearly the same precision as static tests. For example, in test #92, the high frequency standard deviation for r1 data was equal to 14.052 inches (0.3569 meters). Other values for high frequency standard deviations of DiveTracker data points are found on the r1 and r2 distance graphs in Appendix A. Overall, the high frequency standard deviation values for dynamic tests were less than four percent of the mean measured ranges with only one exception; test #91 has a standard deviation for r2 high frequency data equal to five and a half percent of the mean range calculated. These results compare well with the standard deviations from static tests which were less than two percent of total range calculated by the DiveTracker system. Hence, the high frequency portion of dynamic DiveTracker-generated-distances have a similar dense distribution of positional data points as those found in static tests.

2. Longer Range Dynamic Tests

Dynamic experiments conducted at longer range were completed in order to judge the tracking ability of the DiveTracker system over greater distances than previously examined. The longer ranges provided further important information concerning DiveTracker performance characteristics and limitations. High frequency studies were also done on longer range dynamic tests to see if the dense data point distributions from earlier testing could be replicated at greater ranges. As in previous experiments, instantaneous analysis of the DiveTracker positioning system was also performed by observing the DiveBase real-time visual display; the DT1-D-S module's approximate physical location was matched visually by an observer standing on the MBARI piers against where the DiveBase marked the mobile unit's position relative to the baseline.

Figure 63 displays the equipment configuration for tests #121 and #124, conducted in the Moss Landing Harbor Basin Channel next to the MBARI pier facility. The basestation was placed on the east pier with a 40 foot (12.192 meters) separation between baseline sonar transponders. The mobile unit was mounted in a row boat which was maneuvered along various paths relative to the baseline. Figures 64 and 65 are graphs showing the data points collected from test #121 in which the row boat traveled perpendicular to the baseline. As was seen in similar tests done previously at shorter range, the DiveTracker system follows the path of movement of the DT1-D-

S module without difficulty. As the range between the mobile unit and the baseline transponders increased, the range circles on the graphs in Figures 64 and 65 sloped upward as expected. The DiveTracker system's accurate tracking of the mobile unit was also observed on the DiveBase visual monitor. In this experiment the maximum distance measured by the moving DiveTracker unit was about 200 feet (60 meters). The physical limitations of the Moss Landing Harbor prevented further travel at greater distances along a perpendicular path.

Figures 66 and 67 are graphs showing the data points collected from test #124 in which the row boat traveled parallel to the baseline. The results of this test were not as predictable as test #121. The DiveTracker system traced the movement of the DT1-D-S module but had difficulty providing accurate positions when the mobile unit was greater than approximately 330 feet (100 meters) away from the basestation transponder #2. As can be seen in Figure 66, there was no loss in tracking for the DiveTracker r1 distances. However, the r2 ranges found in Figure 67 are observed to jump off the graph as the row boat past about 110 yards (100 meters) from station #2. This is another example of the DiveTracker system producing enormous false distances when performing outside the system's limitations. The DiveBase display at the basestation appeared as a frozen picture when the DiveTracker system lost track of the mobile unit position during test #124. Invalid distances resulting from multiple-path and bottom-reflected sonar returns were observed on the DiveBase visual monitor to cause the mobile unit icon to move radically across the screen.

The specific case of data drop-out discovered in test #124 is particularly baffling because the previous problems associated with pier obstructions and unmounted sonar heads were corrected prior to conducting this experiment. After consulting with the Desert Star System owner, Mr. Marco Flagg, who is the inventer of the DiveTracker system, it was concluded that the 100 meter range limitation found in test #124 and other dynamic experiments was a result of the shallow Moss Landing Harbor Channel depth, which was discovered to be only about 30 feet (10 meters). The shallow channel deflected the normally omnidirectional path of a traveling sonar signal and thus caused multiple sound returns and a general DiveTracker system degradation.

Further dynamic tests were completed to identify a data drop-out zone in which the DiveTracker system either stopped calculating distances due to a loss in tracking or produced

erroneous data. Experimental results pointed towards DiveTracker r2 calculated ranges being much more susceptible to producing incorrect position data from multiple-path and bogus sonar returns. This phenomena causes the symbol for the mobile unit on the DiveBase visual display to randomly jump over great distances. Several more dynamic tests were done to define a "window" in which the DiveTracker system could produce reliable position data. Figure 68 contains a map of the Moss Landing Harbor Channel with areas marked where the DiveTracker system lost track of the moving DT1-D-S module.

Numerical analysis was also performed on the longer range dynamic experiments. The high frequency portions of the data were processed to find and compare standard deviation values. Once again, the high pass filter programs described above were utilized, producing the plots found in Figures 69 through 72. Because of the enormous false distances produced by the DiveTracker system at the outside limits of the performance window, the high frequency standard deviations were divided by the mean value of the filtered distances produced by the "highfilter.m" program. The standard deviation values were found to be less than four percent of the mean value for DiveTracker distances calculated over the duration of each dynamic experiment. For example, in test #121, the high frequency standard deviation for r1 data was equal to 20.232 inches (0.5138 meters). These results prove that the high frequency portion of dynamic DiveTracker-generated-distances have a similar dense distribution of positional data points as those found in static tests. This leads to the conclusion that the DiveTracker system is capable of tracking a moving AUV with nearly the same precision as a stationary target.

C. EXPERIMENTS USING VARIABLE CONFIGURATION FILE VALUES

Further experiments conducted at the MBARI Moss Landing pier facility entailed tests in which selected configuration file adjustable values were varied to determine any distinguishable difference in DiveTracker system accuracy. These trails were conducted at various tape-measured locations where known distances could be measured using the DiveTracker system. Various adjustments were made to the baseline length and sonar pulse length values found in the configuration file for the SmartDive operating code. Variable depths for the DT1-D-S module were also scrutinized to verify the DiveTracker system's ability to separate the vertical and

horizontal distances between the basestation and the mobile unit. The overall purpose of these experiments was to find the optimal settings for a configuration file to be used in an AUV mine-hunting mission in very shallow waters.

1. Variable Baseline Length Tests

Figure 73 contains the equipment set up for tests #130, #131, and #132. In this series of experiments, the mobile unit was placed in a stationary location 25.83 feet (7.874 meters) away from the basestation transponder #1. These two sonar heads were held in the same fixed positions through out the trials while the second transponder from the basestation was moved to test the effects of a variable baseline length on DiveTracker accuracy. In test #130 the baseline length was 38 feet (11.58 meters). In test #131 that length was shortened to 30 feet (9.144 meters) and the baseline was shrunk again in test # 132 to 20 feet (6.096 meters). As the baseline was varied in length, adjustments to the configuration file value for baseline distance were also made to match the new length.

Accuracy of the DiveTracker system was determined by comparisons of tape-measured distances to those calculated by the sonar system. By taking the differences in these two lengths for each of the test runs, and then comparing the differences of various tests, it was hoped to determine the effect of the varied length of the baseline on DiveTracker precision. Standard deviations of the DiveTracker data points were also checked to monitor any variation in data point density based on the variable baseline distance. And, as always, an observer kept an eye on the DiveBase visual display to verify that the DiveTracker system had placed the position of the mobile unit in the correct location relative to the baseline.

Figures 74 through 79 contain the r1 and r2 graphs from the first set of variable baseline length experiments. These plots are similar to the graphs seen in static experiments; the r1 or r2 distance for each data point appears as a circle and a line connects the data points logged over the duration of the experiment. A slight distinction was found between the accuracy of a 38 foot (11.58 meters) baseline and that of the 30 foot (9.144 meters) and the 20 foot (6.096 meters) baseline. In general, the longer baseline measurements tended to be a little bit more precise than those of shorter baselines. For instance, the differences between tape-measure lengths and DiveTracker lengths from the 38 feet (11.58 meters) baseline was 15.433 and 11.614 inches

(0.392 and 0.295 meters) for the r1 and r2 distances respectively. Somewhat greater differences were found in test #132 in which a 20 feet (6.096 meters) baseline produced errors of 18.268 and 13.858 inches (0.464 and 0.352 meters) for the r1 and r2 distances respectively. A check of the r1 and r2 standard deviations produced from the record files of these tests show that the data point distributions were nearly the same regardless of baseline length. In some cases, the standard deviation values were actually smaller for the trials using the shorter baseline. In all cases, the DiveBase visual display correctly placed the mobile unit icon at the DT1-D-S module's actual physical position relative to the baseline .

A second set of variable length baseline experiments were conducted at a longer tape-measured distance to verify the results noted above. Figure 80 is the equipment configuration map for tests #136, #137, and #138. In this experimental set up, the base station transponder #2 was moved farther away from basestation sonar #1 as the testing sequence progressed from 20 feet (6.096 meters) out to 38 feet (11.58 meters). A negligible contrast was found between the accuracy of the various baseline lengths. For example, in test #137, the differences between tape-measure lengths and DiveTracker lengths for the 30 feet (9.144 meters) baseline was 0.039 and 8.307 inches (0.001 and 0.211 meters) for the r1 and r2 distances respectively. Similar differences were found between the tape-measured and DiveTracker calculated positions in test #136. A 20 foot (6.096 meters) baseline used in test #136 produced errors of 1.323 and 5.236 inches (0.034 and 0.133 meters) for the r1 and r2 distances respectively. The standard deviations for r1 and r2 data from these longer range tests show that the data point distributions were nearly the same regardless of baseline length. For example the standard deviation of r1 distances in tests #136 and #137 were equal to 5.231 and 4.059 inches (0.1329 and 0.1031 meters) respectively.

It was therefore concluded that longer baselines improved the accuracy of the DiveTracker system, but only marginally at the relatively short ranges in which these experiments were conducted. Since salt-water testing was restricted to the area within the MBARI pier facility, the variable length baseline experiments were not as conclusive as previously expected. A difference in accuracy based on baseline length was not considered significant in this testing area. Interestingly enough as a side note, the r2 data recorded during test #138 experienced some unstable variations. It was quickly determined that this DiveTracker system degradation was

caused by the familiar pier masking problem which, unknown to the test personnel, had once again partially blocked a direct sonar path between the mobile unit and basestation transponder #2. Another interesting side note was the improvement in DiveTracker precision during the longer tape-measured trials. With the exception of the flawed r2 data from test #138, the differences between tape-measured ranges and DiveTracker-calculated values were consistently smaller for the second set of variable baseline length tests.

2. Variable Pulse Length Tests

Another set of static tests, which necessitated changing a configuration file adjustable value, involved the experiments to examine the effect of variable sonar pulse length. Since the length of time a transponder uses to send a sonar pulse signal effects the minimum range detectable by an acoustical positioning system, it was expected that sonar pulse length may determine minimum detection range for the DiveTracker positioning system. However, zero length static trials described earlier, using the preset pulse length preprogrammed in to the configuration files by Desert Star systems (4000 milliseconds), had proven that there was not a minimum range of accurate DiveTracker performance. Accordingly, variable pulse length tests were not conducted at a zero length distance, but instead at a short, tape-measured range to examine if the changeable sonar pulse transmitting time had any effect on DiveTracker system precision.

Figure 87 contains the equipment set up for tests #155 through #160. All three transponders were held in fixed positions through out this entire set of experiments. Before each test run, the configuration files which control the operation of the SmartDive program in both, the basestation and the mobile unit, were adjusted to contain matching pulse length values. Each test run used a different pulse transmit time. The sonar pulse lengths were adjusted, from 4000 to 1000 milliseconds in increments of 500 milliseconds, during this series of test runs while all other variables were held constant.

Results from the variable pulse length experiments were analyzed in a similar manner to the test results from variable baseline distance tests; accuracy of the DiveTracker system was determined by comparisons of tape-measured distances to positions measured by the sonar system. Variations in accuracy from various tests were used to determine the effect of changing

the sonar pulse duration on DiveTracker precision. Standard deviations of the DiveTracker data points were also checked to monitor any difference in data point distributions due to the variable pulse length.

Figures 88 through 99 contain the r1 and r2 position graphs from the variable pulse length tests. These plots are just like the graphs seen in static and variable baseline length experiments. The sequence of data points recorded during a test produced a nearly straight line on the plots found in Figures 88 through 99. There was no distinguishable difference between the accuracy of longer sonar pulses and that of the shorter signals. Unlike the variable baseline test measurements, which showed a slight trend towards more precision from a favorable longer baseline length, the adjusted pulse times did not display any type of trend towards better or worse accuracy. For instance, in test #155 , in which the sonar pulse time was set for 4000 milliseconds, the differences between tape-measured lengths and DiveTracker calculated lengths was 2.402 and 10.709 inches (0.061 and 0.272 meters) for the r1 and r2 distances respectively. In comparison, a shorter pulse length of 2500 milliseconds used in test #158 produced almost identical results. In test #158, the differences between tape-measured lengths and DiveTracker calculated lengths was 2.953 and 4.606 inches (0.075 and 0.117 meters) for the r1 and r2 distances respectively.

Analyzing the standard deviations recorded in Figures 88 through 99 show that the data point distributions were nearly the same through out this series of experiments. As it has come to be expected, the r2 standard deviation values were about twice the amount of the r1 standard deviations. Since the length of the sonar pulse transmitting time did not have an effect on either the standard deviation of data points or the difference between the DiveTracker calculated distances versus the tape-measured ranges, it was subsequently concluded that sonar pulse length will not effect AUV navigation in an environment such as that found at the MBARI pier facility.

3. Variable Depth Tests

The final set of experiments examined variable depth testing. The experiments were done in order to verify that the DiveTracker system could separate vertical distances from r1 and r2 ranges and hence, maintain a x-y positional fix when an AUV dives below the depth of the baseline. The variable depth testing procedure required the mobile unit to be positioned in a location which was horizontally fixed relative to the baseline. The transponder connected to the

DT1-D-S module was lowered to the bottom of the Moss Landing Basin and then raised back up again. The depth of the water at the MBARI piers was approximately 20 feet (6.096 meters). The personal computer connected to the DT1-D-S module recorded the r1 and r2 distance data from the mobile unit while the change in vertical distance occurred. These experiments were completed at two different locations with in the MBARI pier facility which are marked in Figures 73 and 80.

Simple numerical analysis was performed on the r1 and r2 distances recorded during the variable depth tests to insure the close density of data points was maintained during the experiment. The relationship between standard deviation values as a percentage of overall range from these tests were compared to those static tests performed earlier. As a means of additional analysis, an observer watched the DiveBase visual display at the basestation to verify that the DiveTracker system held the position of the mobile unit in the same fixed horizontal location relative to the baseline, regardless of depth.

Figures 100 through 103 are the r1 and r2 distance graphs from tests # 133 and #139 in which variable depth tests were accomplished. Because the mobile unit was held at the same horizontal distance away from the basestation transponders, a change in depth should not appear on these graphs. The plots should look just like a static experiment, even though the range from the baseline to the DT1-D-S module is increasing due to the extra vertical range added when lowering the mobile unit into deeper water. Since the DiveTracker system is advertised to eliminate this added vertical distance from r1 and r2 ranges, the graphs in Figures 100 through 103 should appear as straight lines. In fact, with the exception of the r2 data from test #139, the plots are almost flat lines across the page. The one exception, that of the r2 data from test #139, is a result of the same blocked transponder found in tests #136 through #138 which was masked by a pier piling . Tests #136 through #139 were done in sequence prior to detecting the partially obstructed sonar path which degraded the DiveTracker system accuracy.

Turning to the analysis of the variable depth tests, the standard deviation values for r1 and r2 data in test #133 were equal to less than four percent of the total distances measured by the DiveTracker system. This value is only slightly higher than standard deviations resulting from static tests. The standard deviation from r1 data collected during test #139 is less than one percent of the total range. The standard deviation from r2 data in test #139 was corrupted by the pier

masking phenomena and was not included in this survey. The mobile unit icon seen on the DiveBase visual display during the experiment remained fixed in it's stationary position regardless of the depth of the mobile transponder. The mobile unit symbol on the radar-like screen display was only seen moving during the early portion of test #139 when r2 data had become slightly unstable. With these favorable results, it was decided that the DiveTracker system did in fact, as advertised, accurately measure horizontal ranges to the DT1-D-S module notwithstanding the change in depth of the mobile unit transponder.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis has examined the accuracy and feasibility of the DiveTracker acoustical navigation system in Autonomous Underwater Vehicle employment. The DiveTracker system uses triangulated sonar pulses to determine the position of a mobile transponder unit (located in the AUV) on a relative grid coordinate system. Both the AUV and the basestation operator receive the AUV position relative to the baseline on a 1 Hertz update rate. Experiments conducted using the DiveTracker basic DT1-D-S module together with the acoustical short baseline/DT1-DRY module basestation have proven that the DiveTracker system is capable of performing precise AUV navigation during mine-hunting missions in the very shallow water near surf zone.

Testing and analysis procedures compared DiveTracker positioning data against know distances. The DiveTracker system was found to have measurement precision to within inches (centimeters) of tape-measured distances over a range of 100 feet (30 meters). For static tests conducted at greater ranges, the collection of data points recorded from the DT1-D-S module was seen in plots as a Gaussian distribution which surrounded the measured mean distance. The DiveTracker system also accurately tracked moving targets during various dynamic experiments. Position data was analyzed and found in most cases to have standard deviations of less than one percent of the total distance measured.

In addition to proving the DiveTracker system's worth for AUV acoustical navigation, the performance characteristics of the sonar mechanism were also explored so to develop a better idea of system reliability and optimum forms of usage. Indirect sonar acoustical paths which repeatedly created poor data were caused by obstructions that block the baseline transponders. This problem can be easily avoided by the careful initial placement of equipment within the line of sight. Fixed sonar head mountings were also discovered to be essential in order to gain reliable results. Configuration file adjustable values, such as transmit power and receiver gain, were fine-tuned for better performance. A copy of the optimal configuration file settings for the MBARI pier facility is included in Appendix B. The shallow water of Moss Landing Harbor channel

created multi-path sonar returns and erroneous position data during experimental testing conducted at ranges greater than 100 yards (110 meters). The effect of this system degradation on very shallow water AUV navigation is still unclear. Further testing of the DiveTracker system performance in the near surf zone environment will be required to solve this latest difficulty.

B. RECOMMENDATIONS

1. Fleet Deployment Concepts

The DiveTracker navigation system used in the Naval Post Graduate School AUV employs a single sonar transponder mounted on the AUV and two transponders in a stationary acoustic Short Baseline (SBL). The first fleet deployment concept, taken from the DiveTracker system's original design purpose for recreational scuba divers, required the SBL transponders to be mounted on the hull of a mothership. The mothership, with the DiveTracker basestation on board, was envisioned safely positioned outside the mine field of interest (see Figure 1).

A second idea for using the DiveTracker system, which used a more stealth conceptualization, involved the SBL placed in position clandestinely by SEAL team or SBU personnel. In this scenario, the DiveTracker baseline is housed in floating, semi-submerged, buoys (see Figure 104). The buoys are dropped by the special operations personnel just outside the mine field boundary. In this manner, a mine-hunting AUV system can be deployed under the cover of darkness in very shallow waters. The special operations personnel are free to depart the littoral area while the reconnaissance of a near surf zone mine field is conducted clandestinely by the AUV.

In the clandestine deployment scheme, the AUV still obtains it's DiveTracker relative position from the baseline but the basestation is no longer completely fixed to one location. In order to prevent ocean currents from carrying the baseline out of the area of interest, the buoys are moored to the bottom. Hence the baseline is only semi-fixed and its position is subject to the arc of the mooring line. In order to recreate a completely fixed baseline using this stealth deployment scheme, a GPS antenna which breaches the surface of the water is mounted on the top of each submerged baseline buoy. In this manner, each baseline buoy has a constantly updating position and the absolute position for the acoustic baseline is maintained. Accordingly,

the AUV position relative to a fixed grid coordinate system is still accomplished and precise mine mapping is capable.

Recently, the DiveTracker system has been envisioned in a Long Baseline configuration in order to improve system accuracy and robustness. Using a LBL system, the DiveTracker navigation network is aided by air-dropped sonar pingers deployed in the actual mine-field. These additional semi-submerged, moored transponders give the Long Baseline Deployment scheme a distinct advantage; precision of the position data is increased by using extra assets to triangulate the AUV. With these extra sonar pingers, the DiveTracker navigation network has a sustainable reliability which can withstand the loss of a baseline unit and still successfully perform it's mission.

2. Further Testing and Experiments

There is a plethora of studies yet to be broached in the field of DiveTracker navigation and subsequent AUV integration. Production and testing of the semi-submerged, moored basestation buoy, for clandestine utilization of the DiveTracker system is just one of the many upcoming topics for future generations of DiveTracker researchers. The extended operational range for the DiveTracker system, which has been forecasted by Desert Star Systems, also promises to provide an opportunity for interesting analysis. Additionally, the Long Base Line deployment scheme discussed above is an exciting DiveTracker topic for upcoming studies.

Finally, the DiveTracker system communication functions are currently being explored by NPS personnel for AUV utilization. Commanding the AUV functions by sending orders from the basestation will be accomplished via sonar signals transmitted by the DiveTracker system. This employment of the Tracker system is currently under research at the Naval Postgraduate School and is expected to be augmented into the Phoenix II AUV in a short time.

APPENDIX A. FIGURES

Figure 1. DiveTracker DT1-D-S Module. From Ref [7].

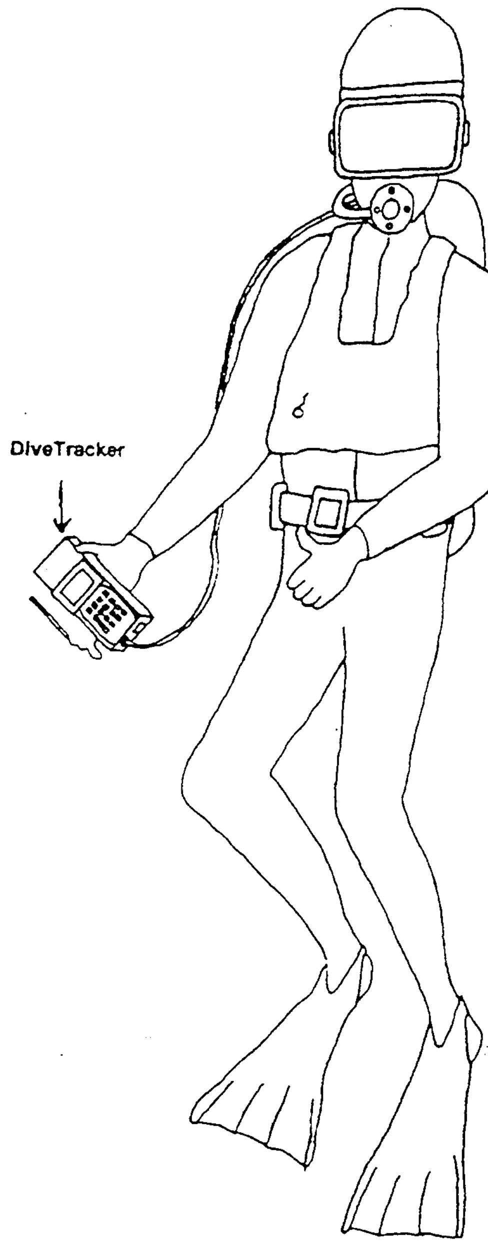


Figure 2. Scuba Diver with the DT1-D-S Module. From Ref [7].

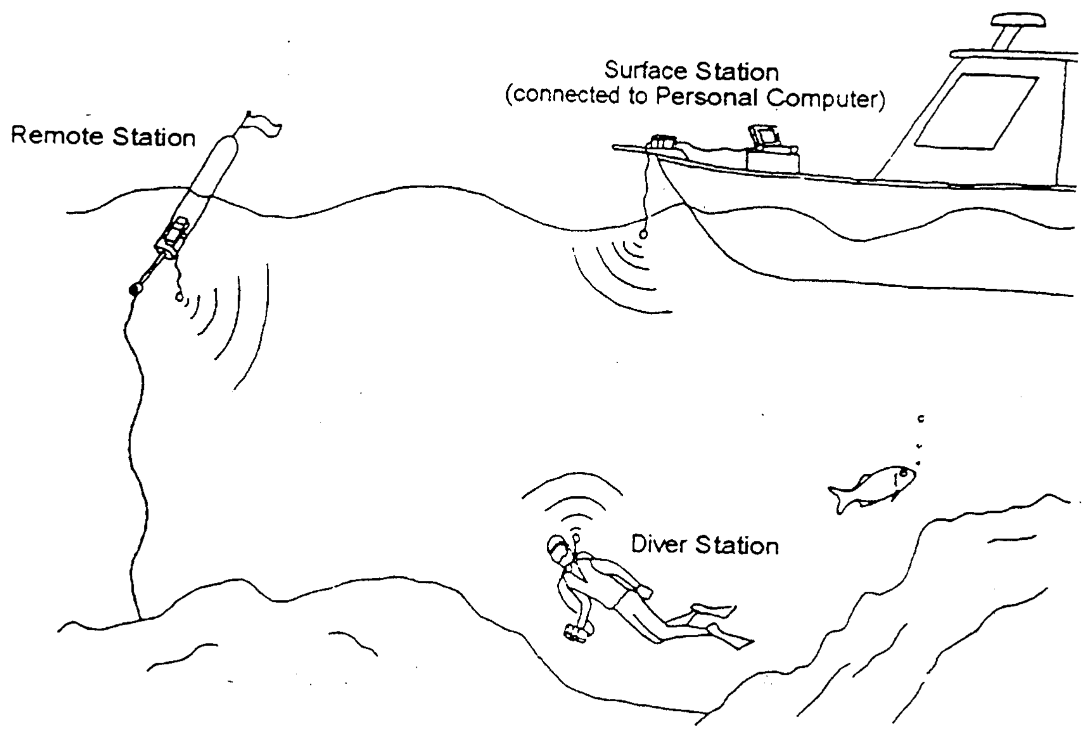


Figure 3. Scuba Diver and Surface Station. From Ref [7].

Figure 4. DiveTracker DT1-DRY Module. From Ref [7].

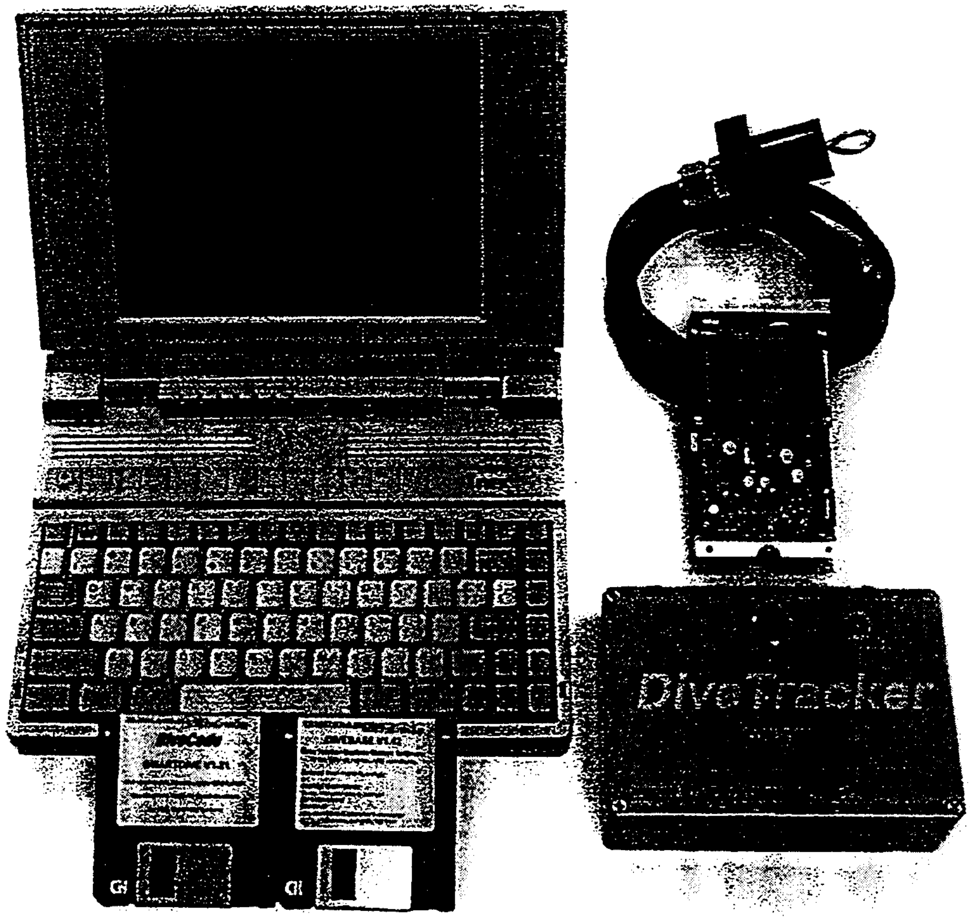


Figure 5. DiveTracker DT1-DRY Module with personal computer. From Ref [7].

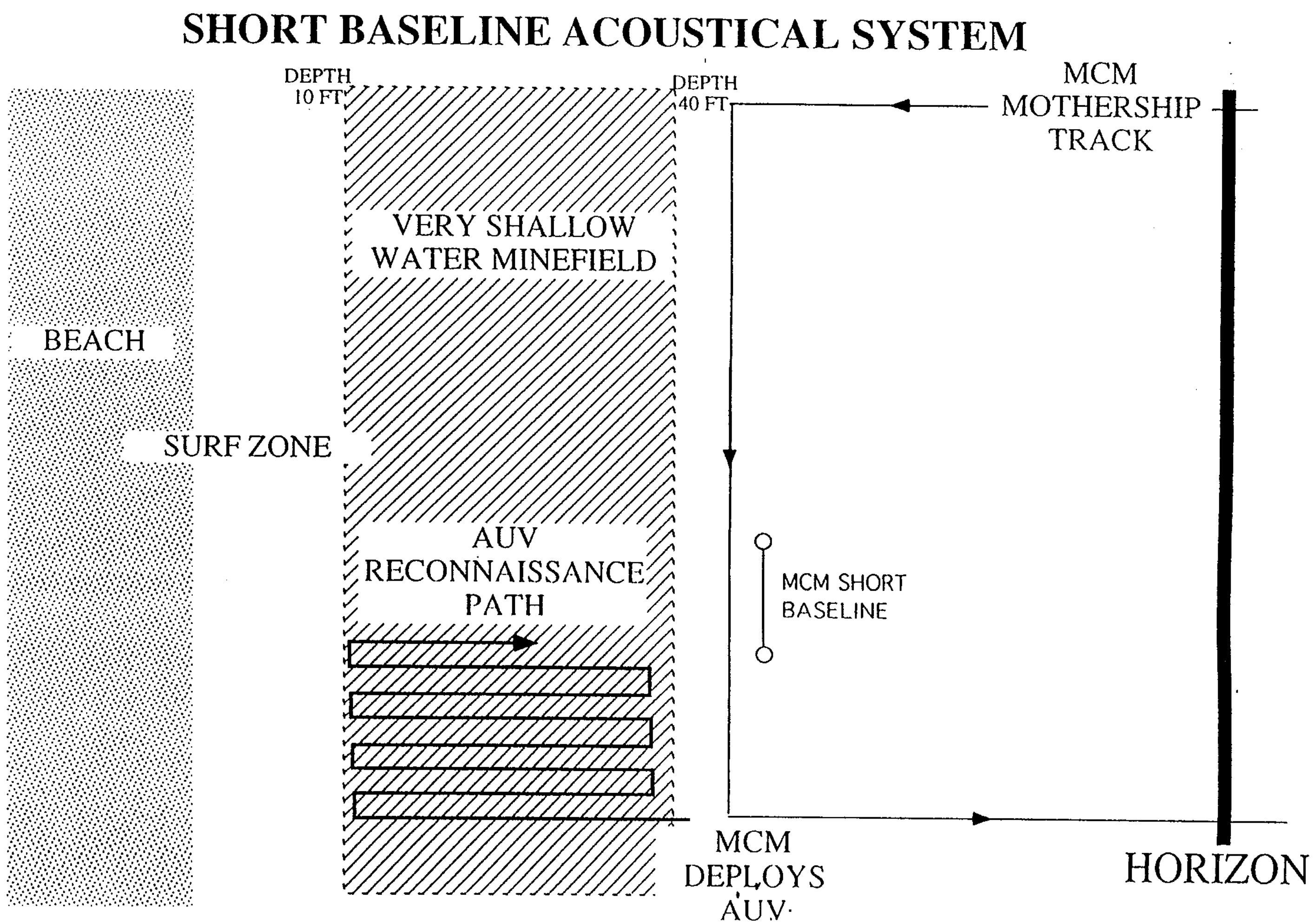
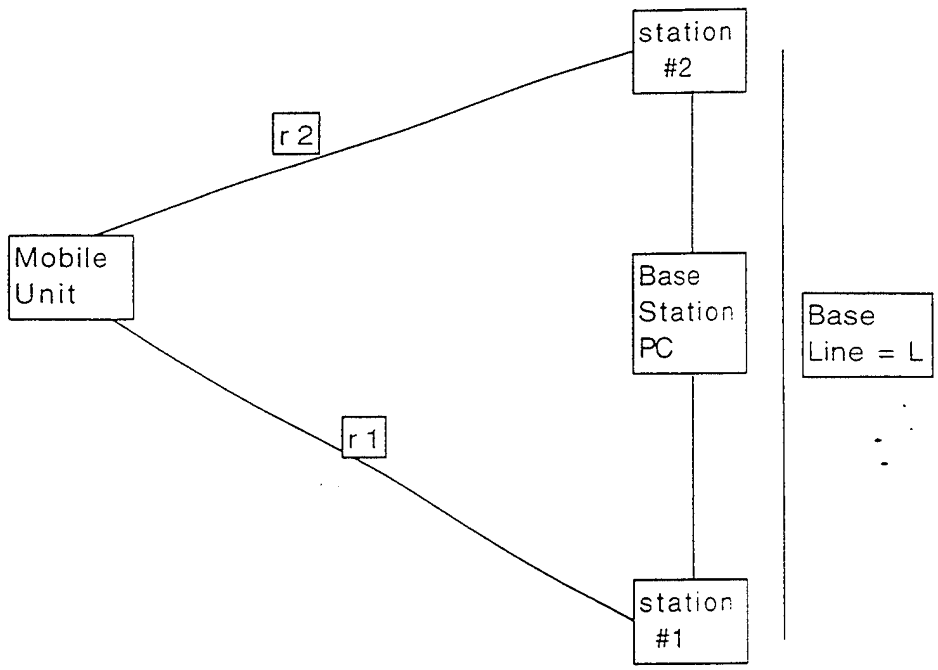


Figure 6. Autonomous Underwater Vehicle and Mothership Positioning in the Near-Surf Zone.



Pinging Sequence: Ping #1 from station #1 to mobile unit = p1
Ping #2 from mobile unit to station#1 = p2
Ping #3 from station # 1 to mobile unit = p3
Ping #4 from mobile unit to station #2 = p4

Base Station Computations: L = known distance
r1 = (p1 + p2)/2
r1 + r2 = p3 + p4
r2 = (r1 + r2) - r1
r2 = p3 + p4 - (p1 + p2)/2

Dive Station Computations: L = known distance
r1 = (p2 + p3)/2
r1 + r2 = p4 + p1
r2 = (r1 + r2) - r1
r2 = p1 + p4 - (p2 + p3)/2

Figure 7. DiveTracker Distance Calculations and Sonar Pinger Sequence.

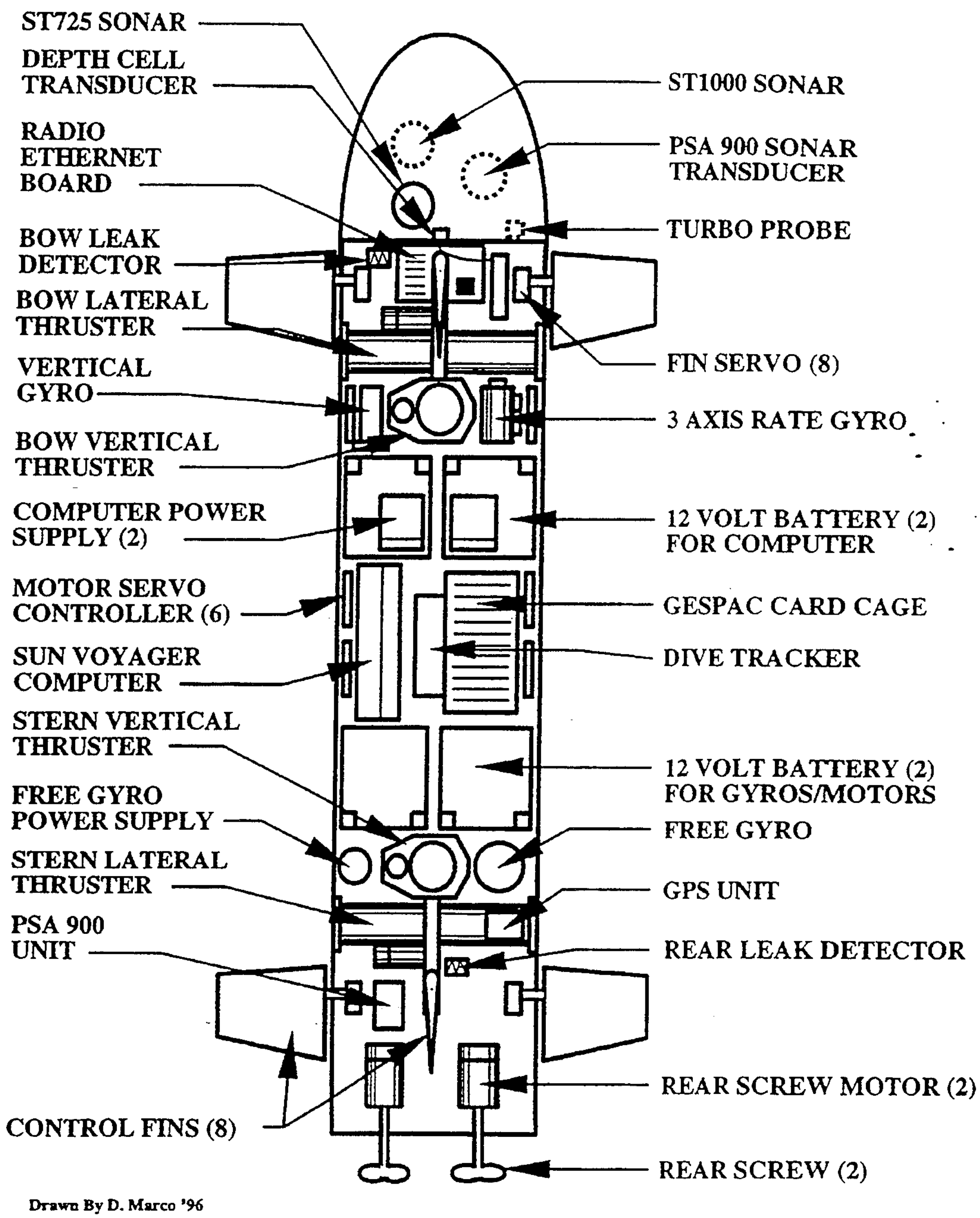


Figure 8. Naval Postgraduate School Phoenix II AUV.

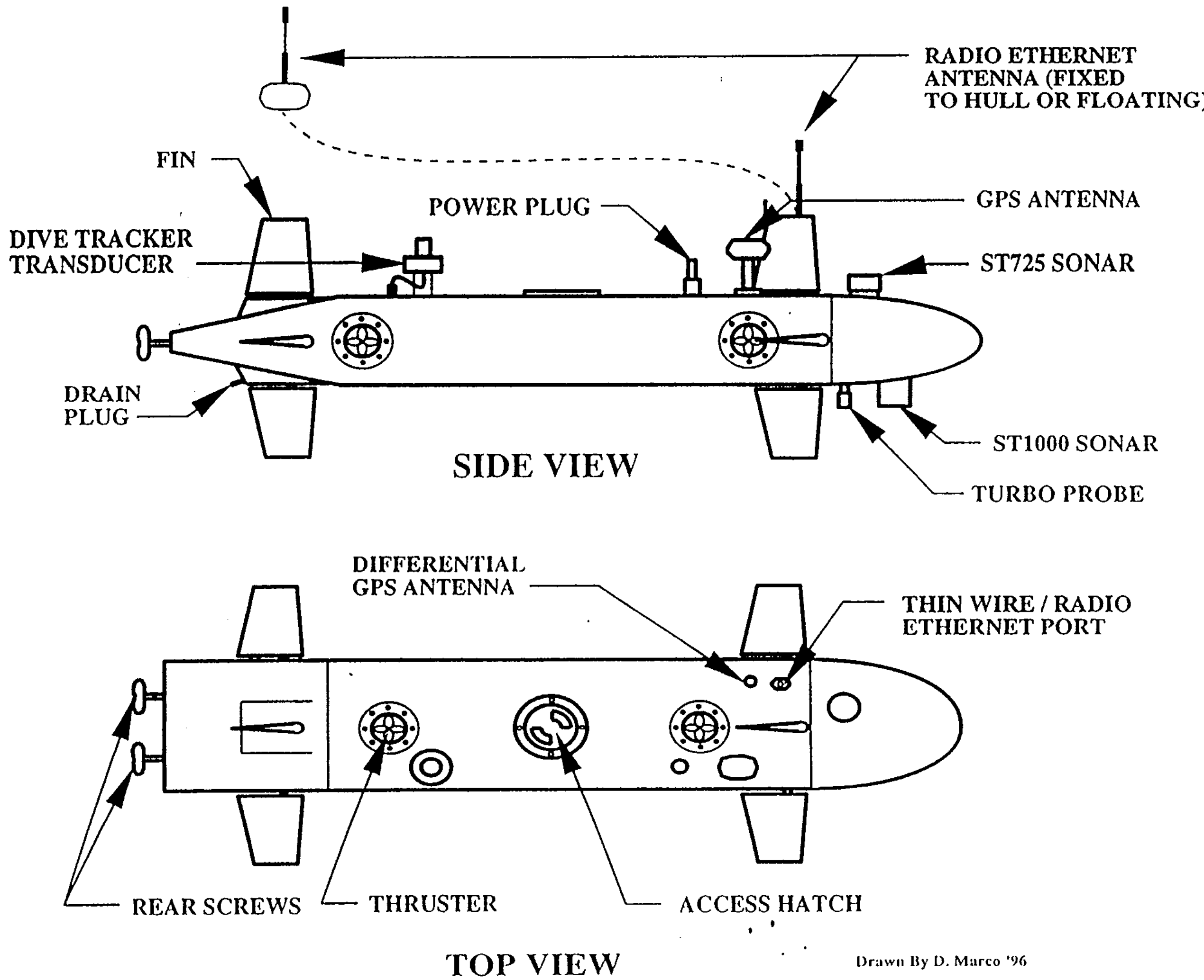
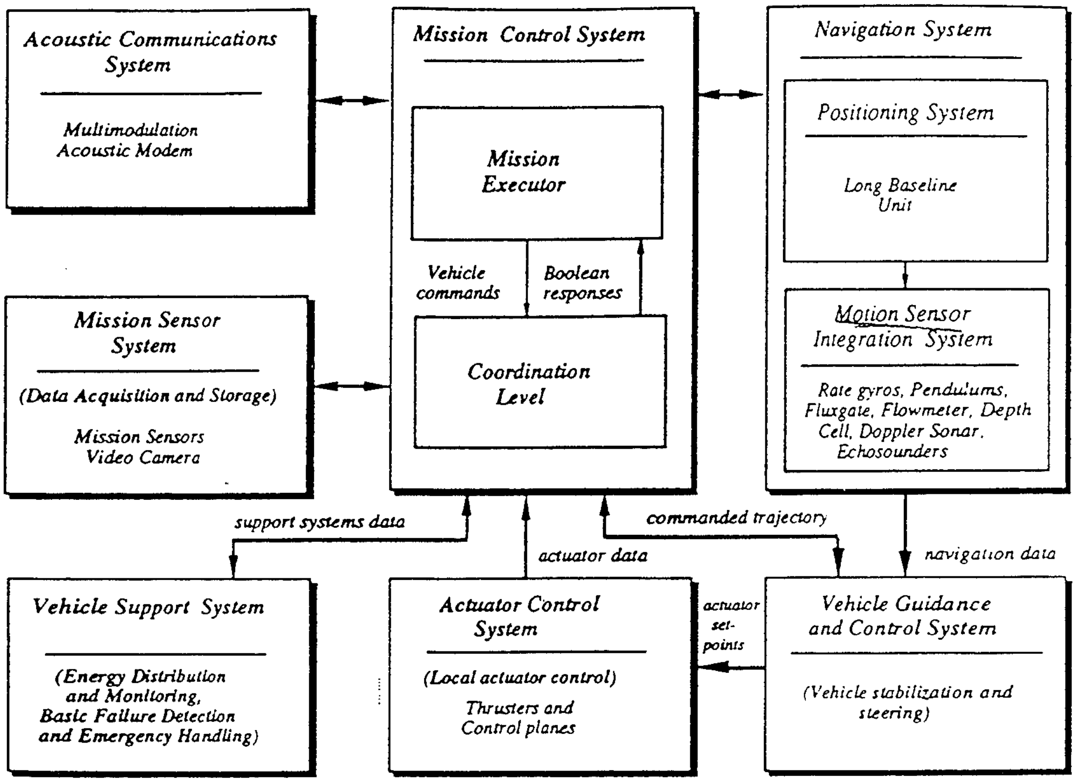


Figure 9. Naval Postgraduate School Phoenix II AUV.



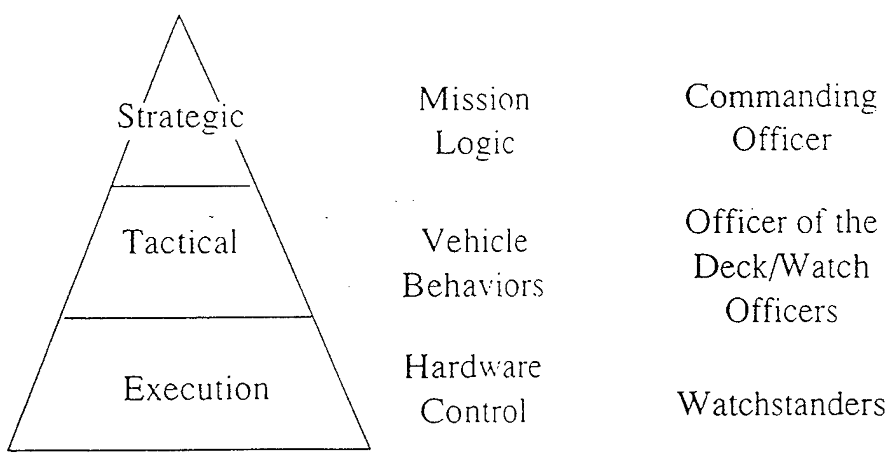


Figure 10. NPS Phoenix II AUV Function Diagram.

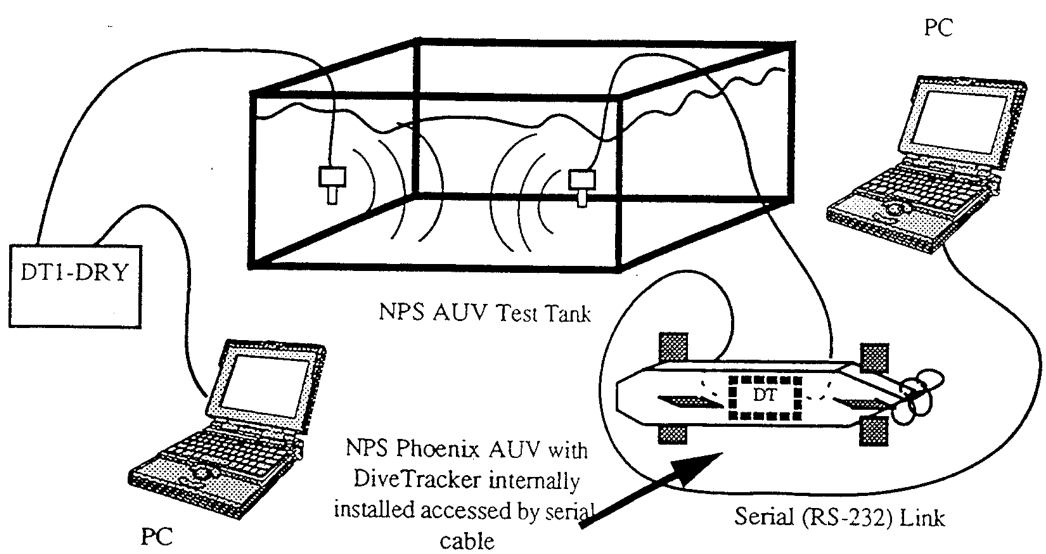


Figure 11. Naval Postgraduate School Test Tank.

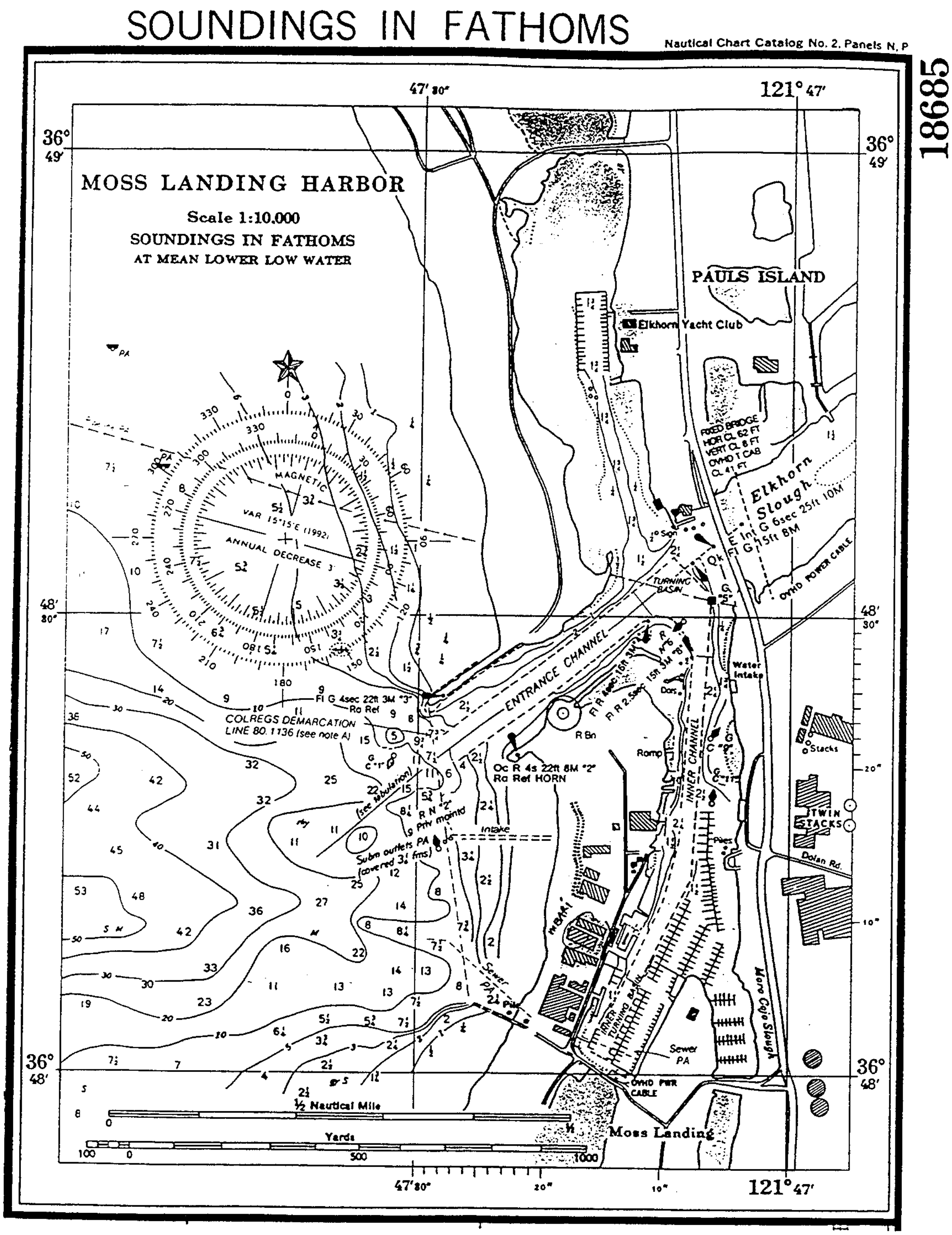


Figure 12. Moss Landing Harbor Map.

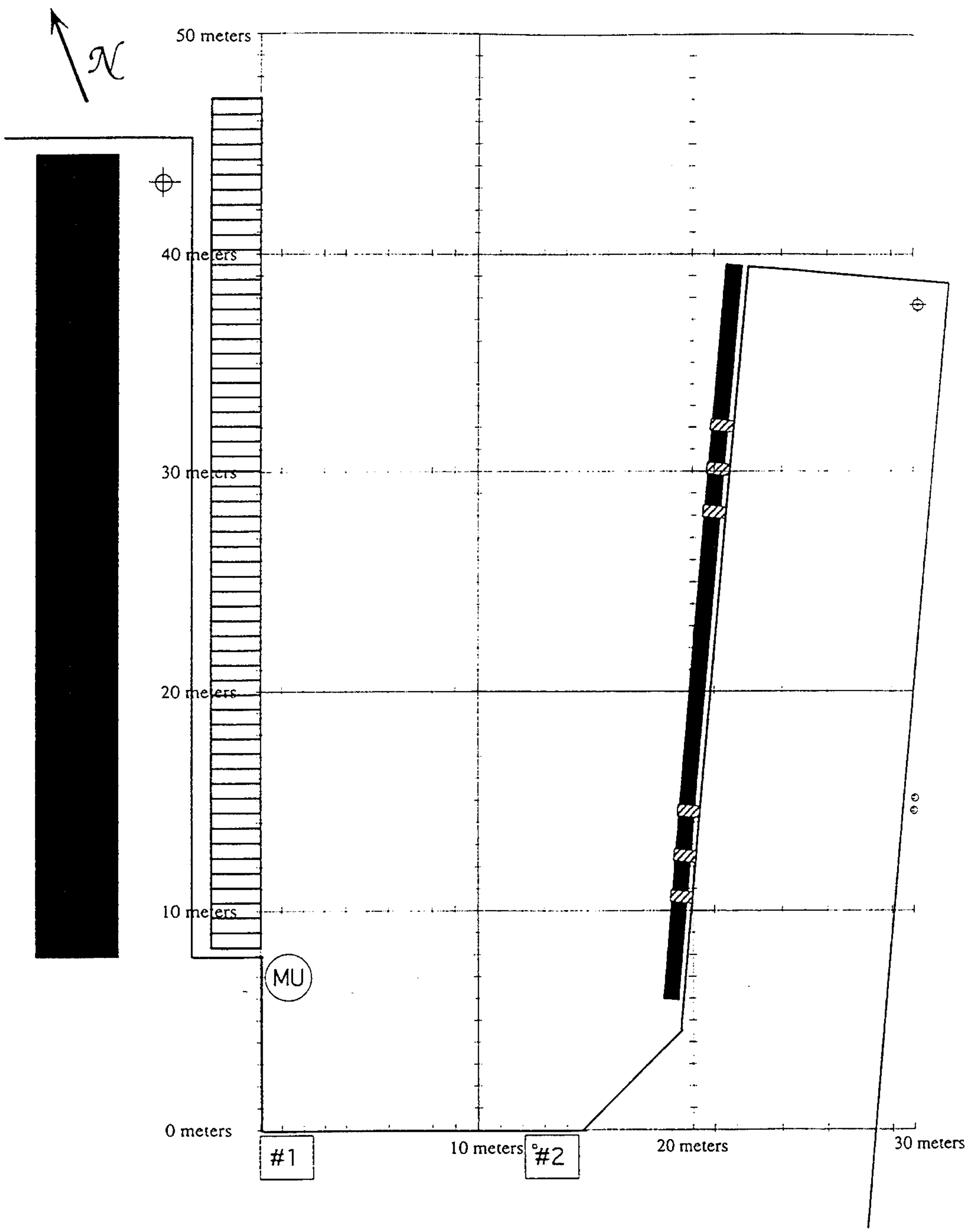


Figure 13. Equipment Set-up for Test #155 at Moss Landing Basin.

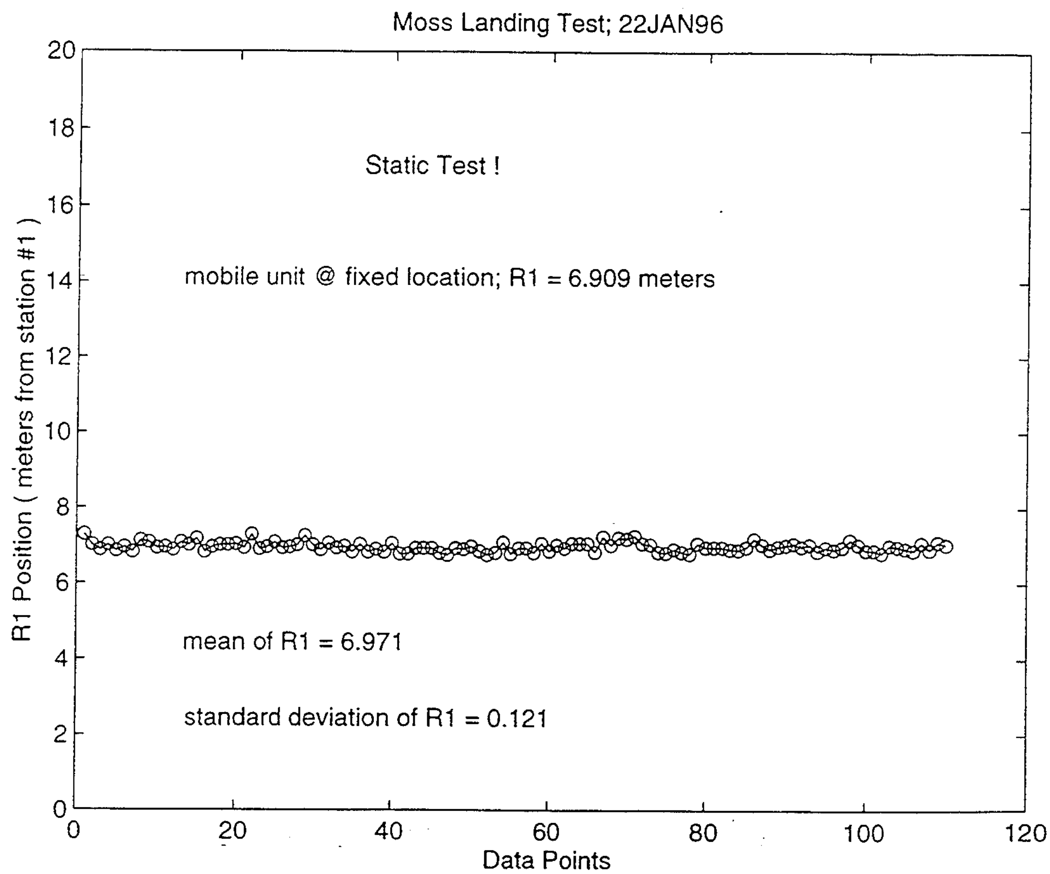


Figure 14. R1 Position Data for Test #155.

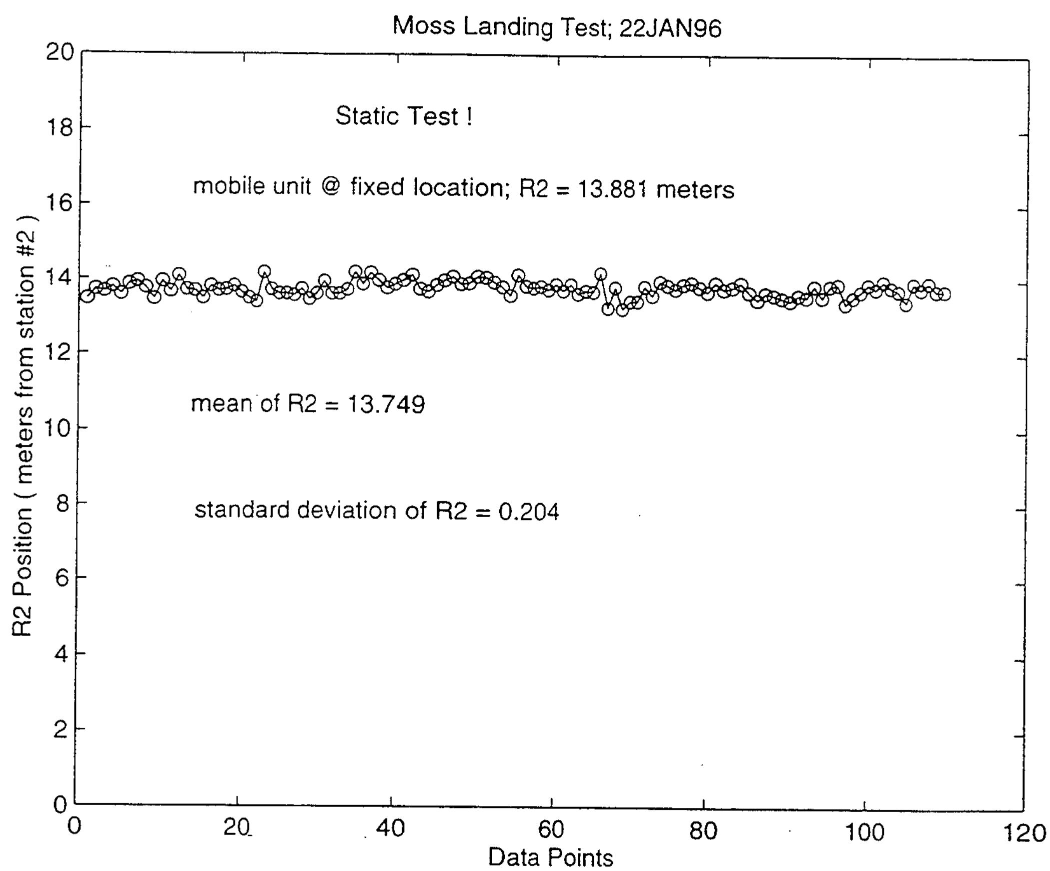


Figure 15. R2 Position Data for Test #155.

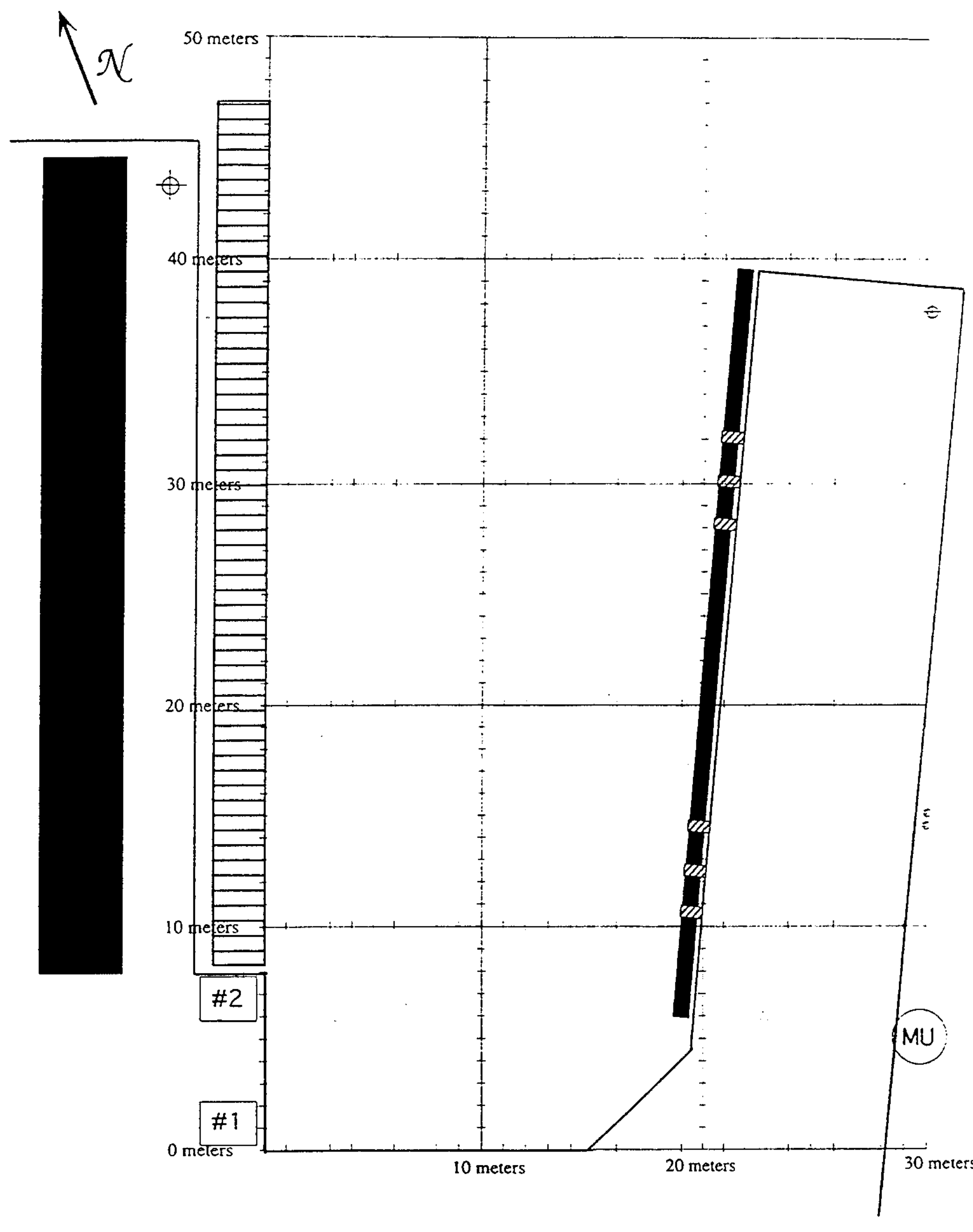


Figure 16. Equipment Set-up for Tests #98 and #99.

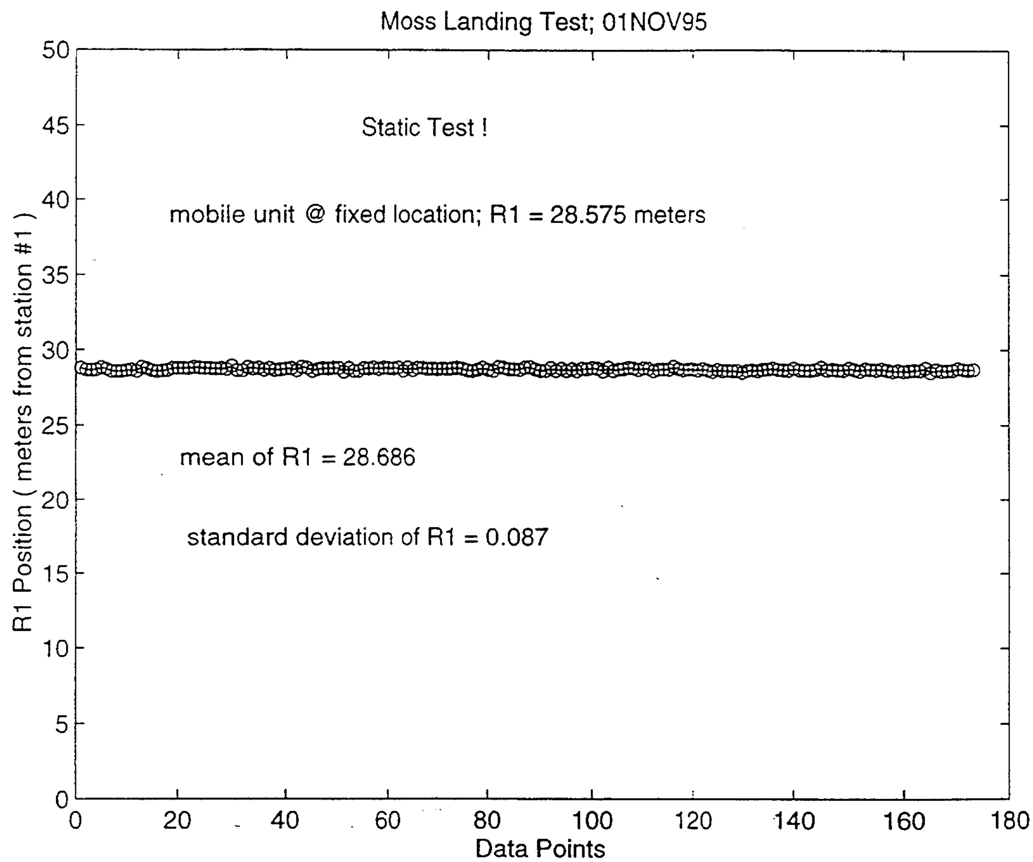


Figure 17. R1 Position Data for Test #98.

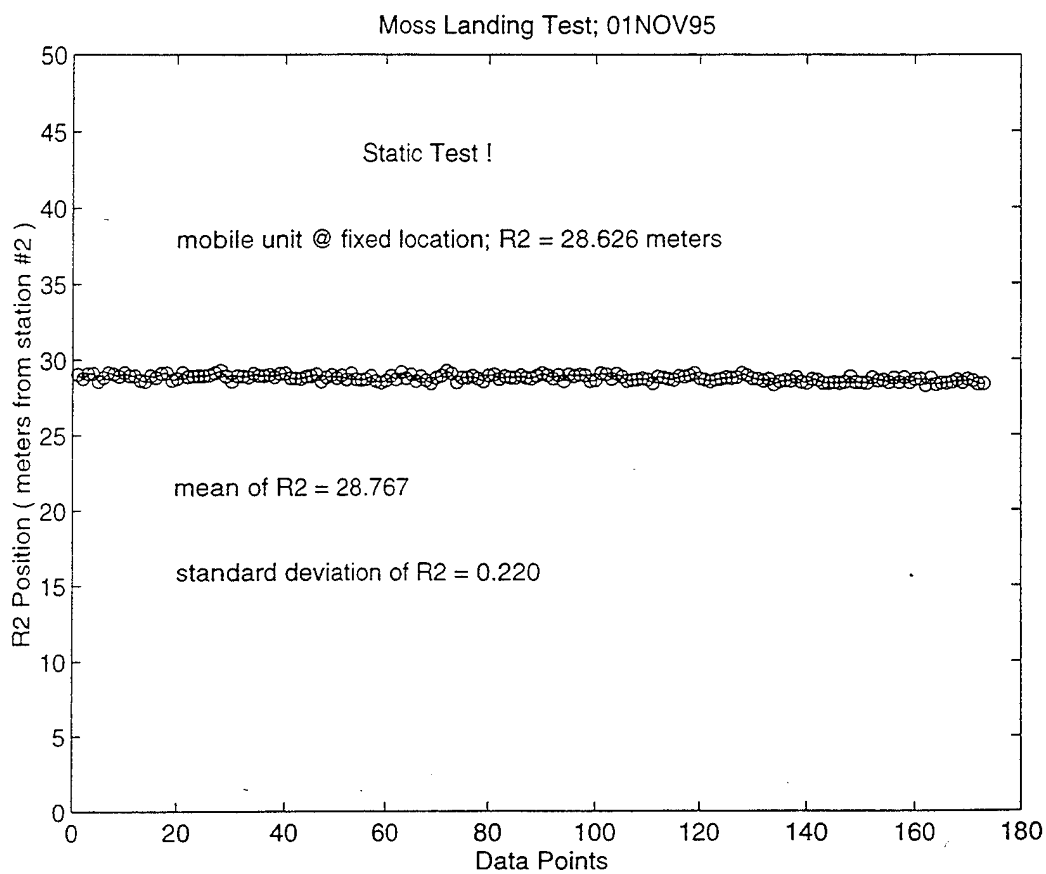


Figure 18. R2 Position Data for Test #98.

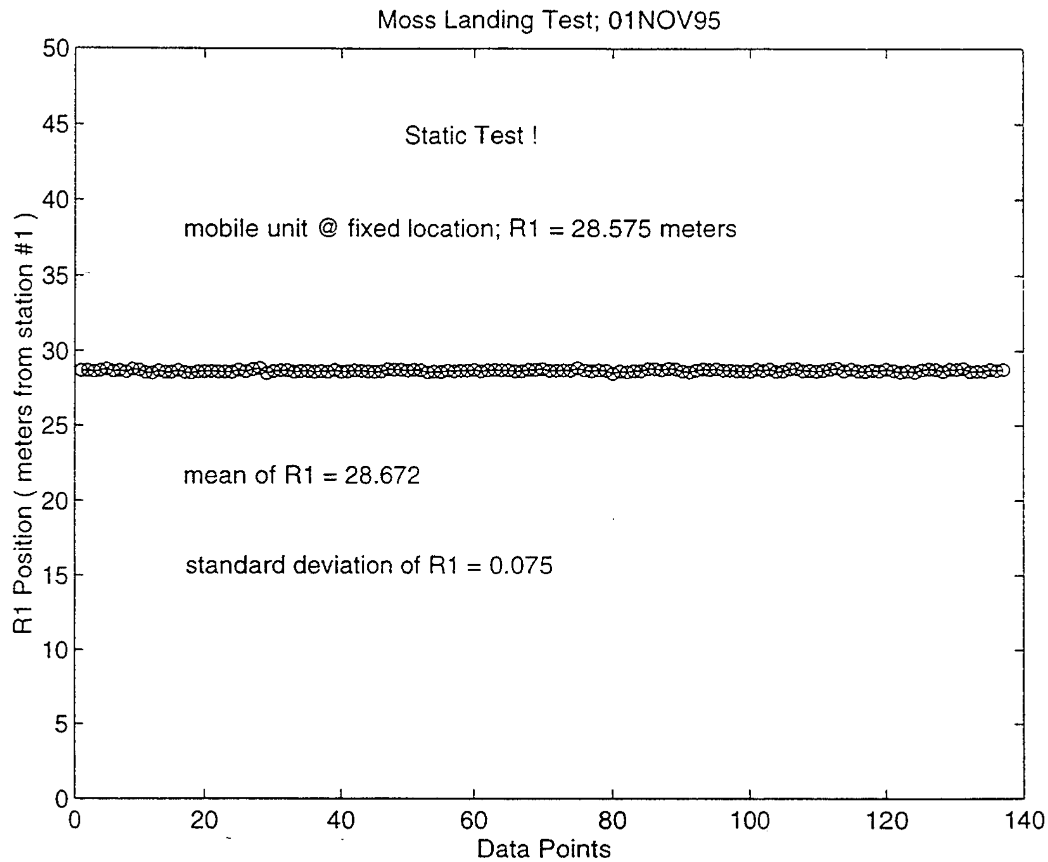


Figure 19. R1 Position Data for Test #99.

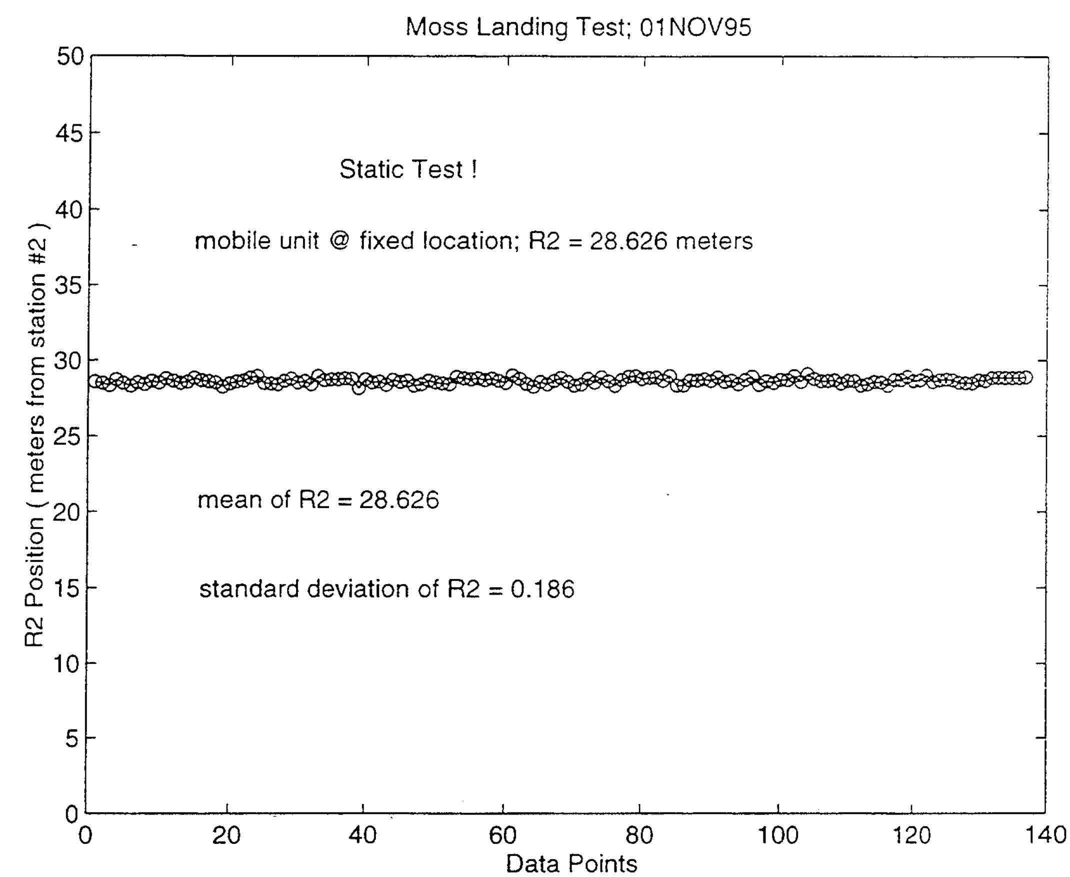


Figure 20. R2 Position Data for Test #99.

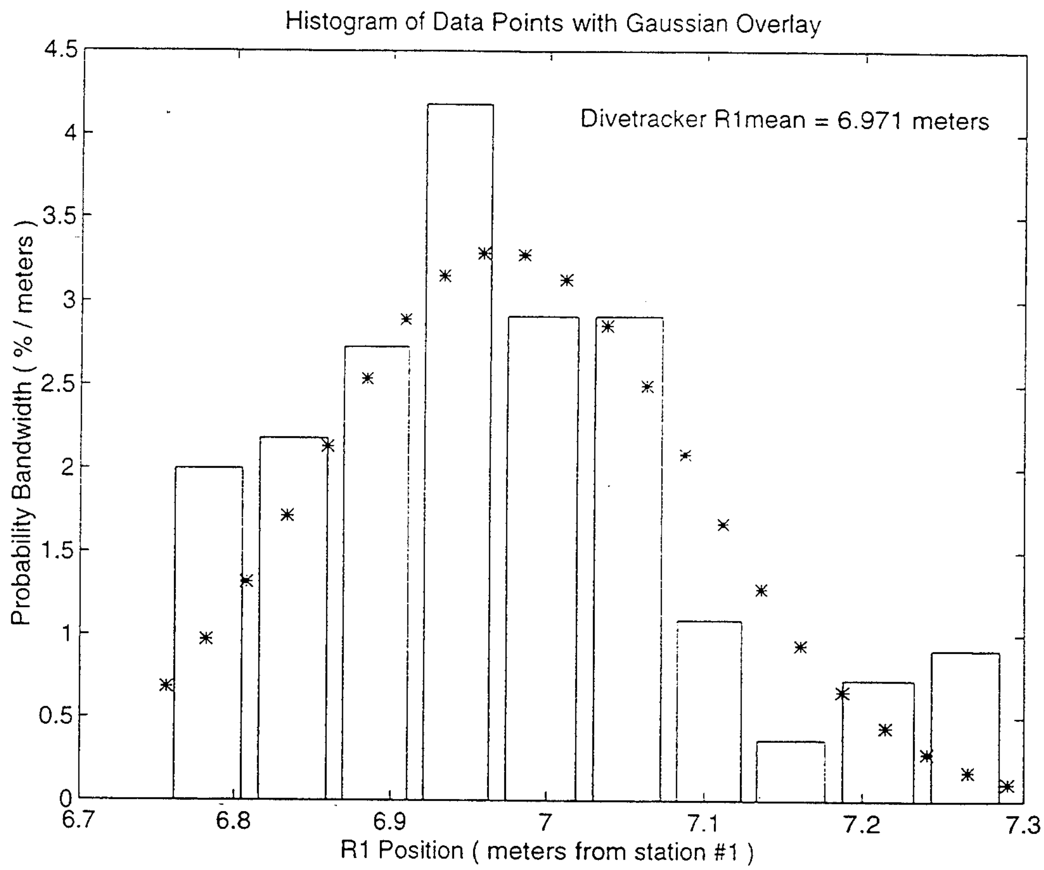


Figure 21. R1 Position Data Histogram for Test #155.

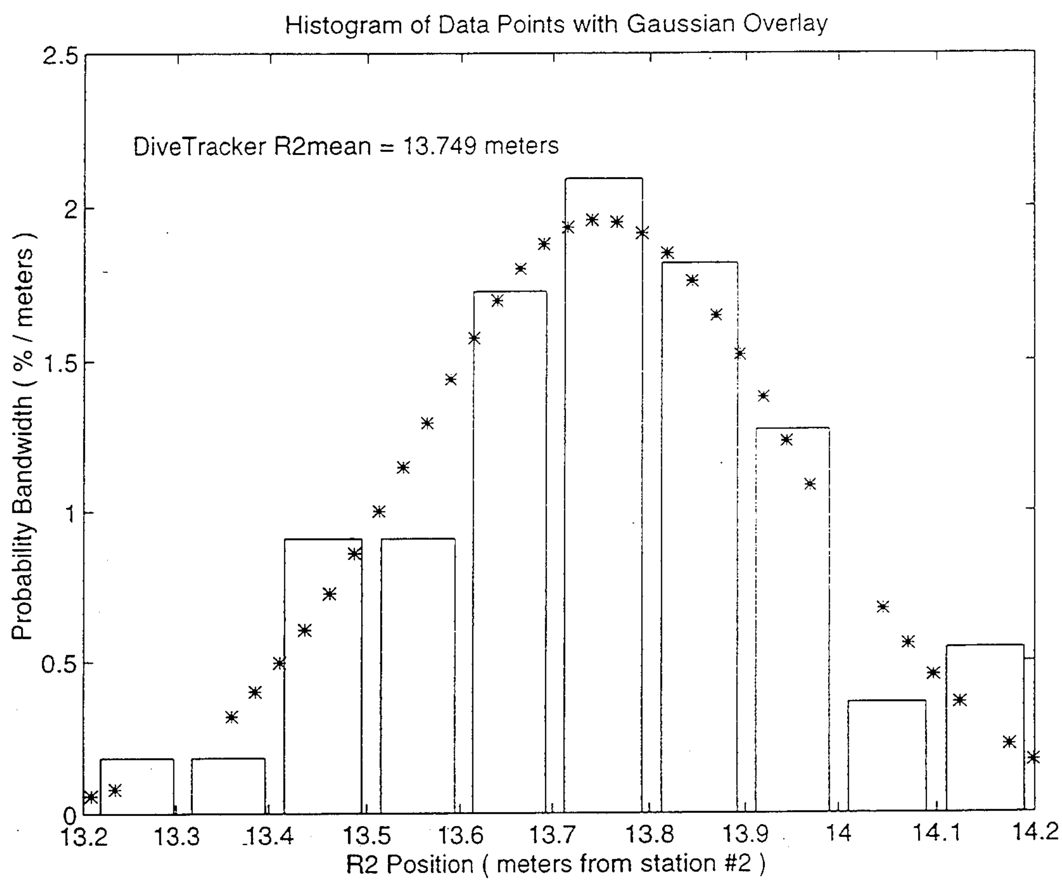


Figure 22. R2 Position Data Histogram for Test #155.

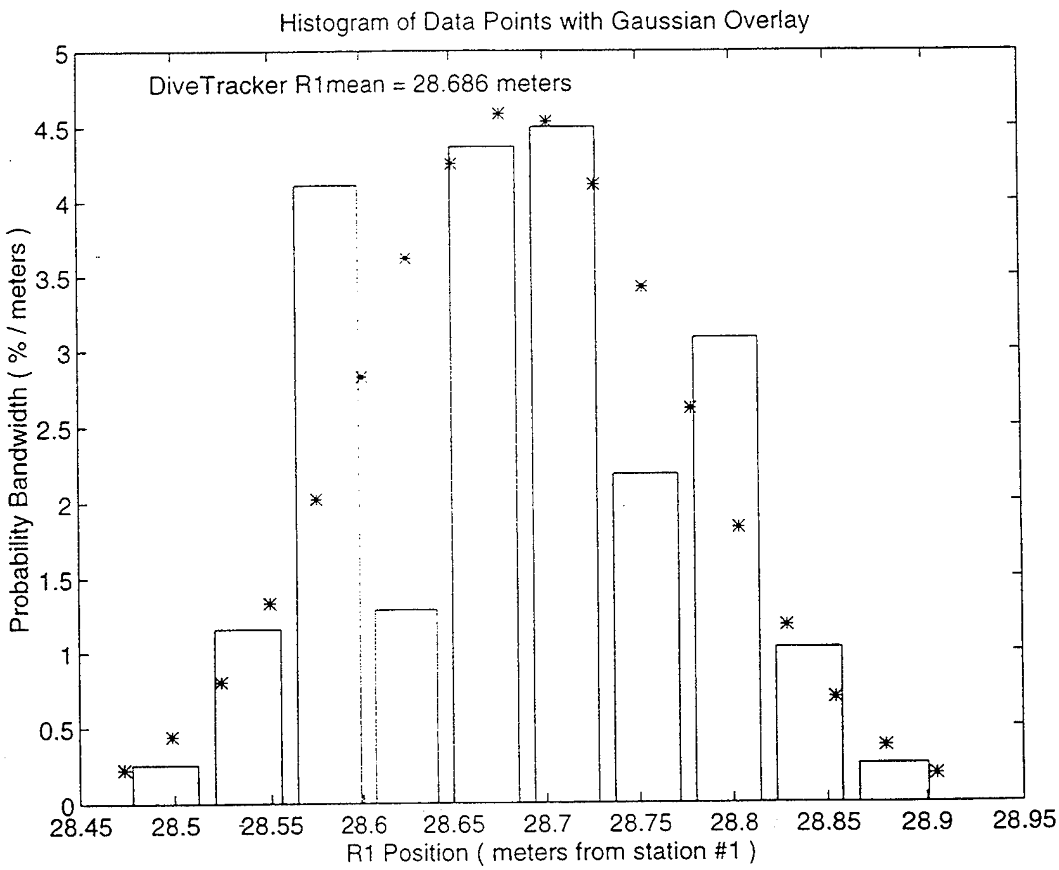


Figure 23. R1 Position Data Histogram for Test #99.

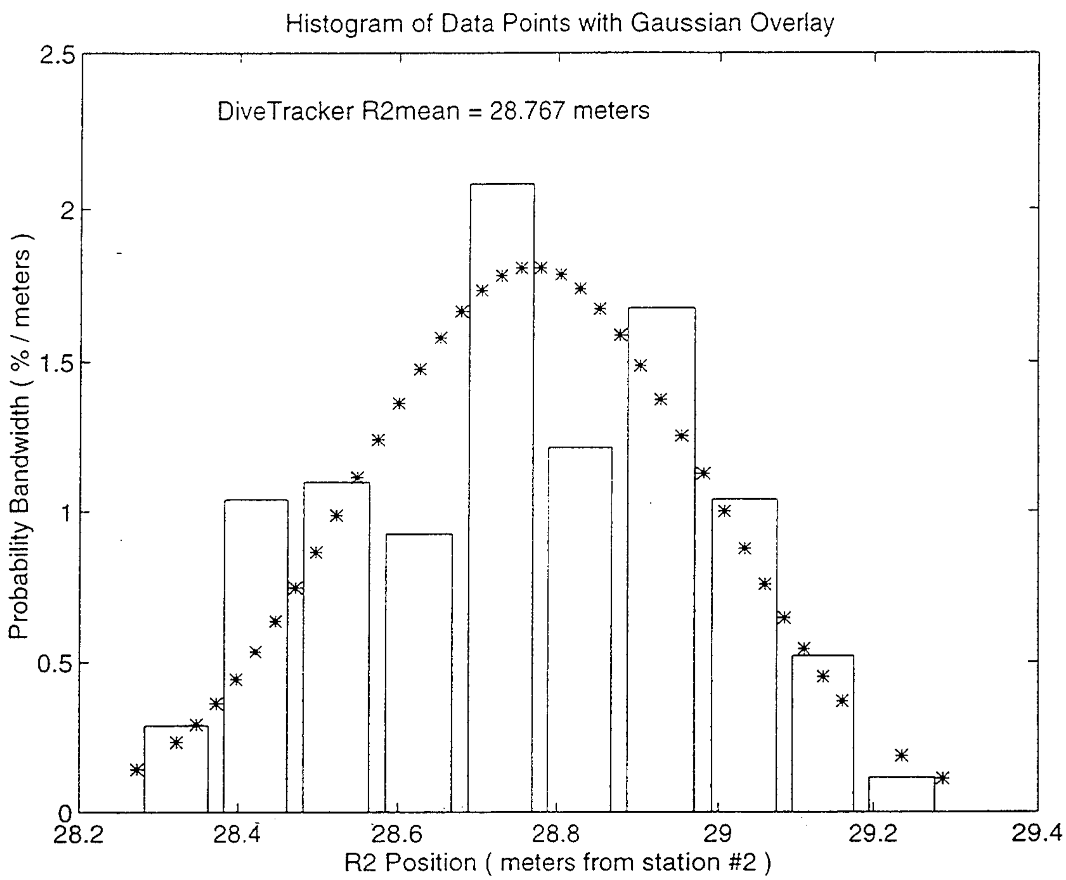


Figure 24. R2 Position Data Histogram for Test #98.

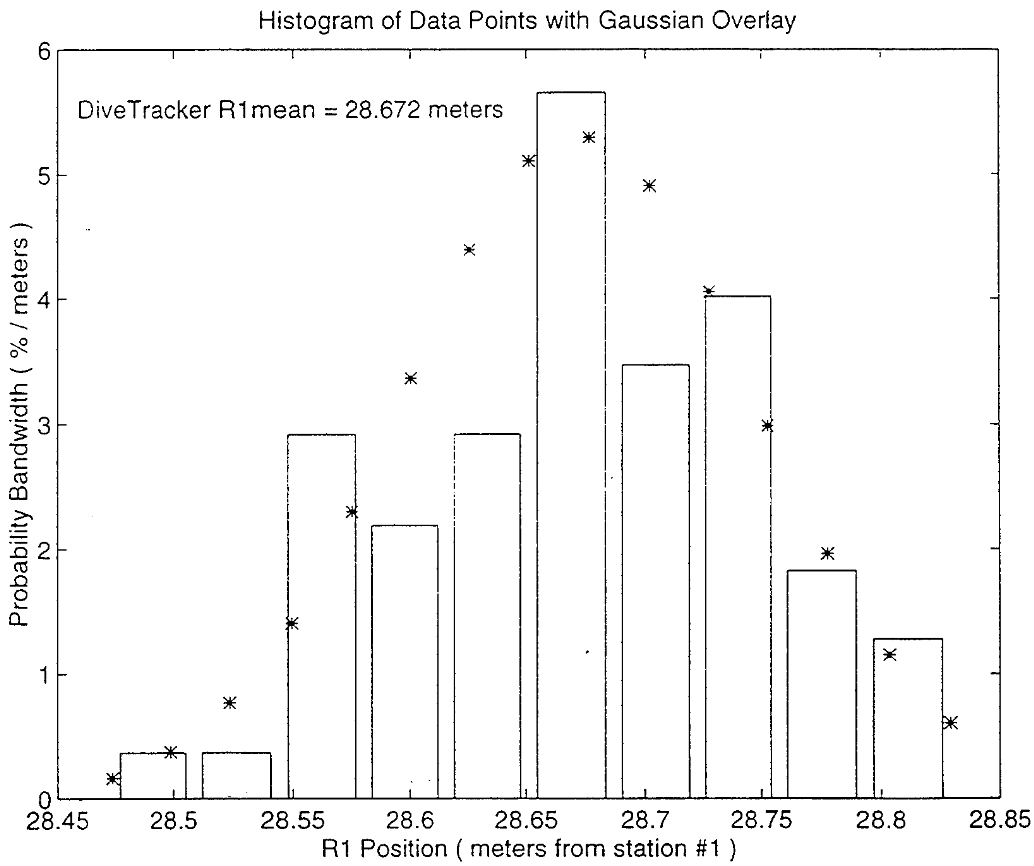


Figure 25. R1 Position Data Histogram for Test #99.

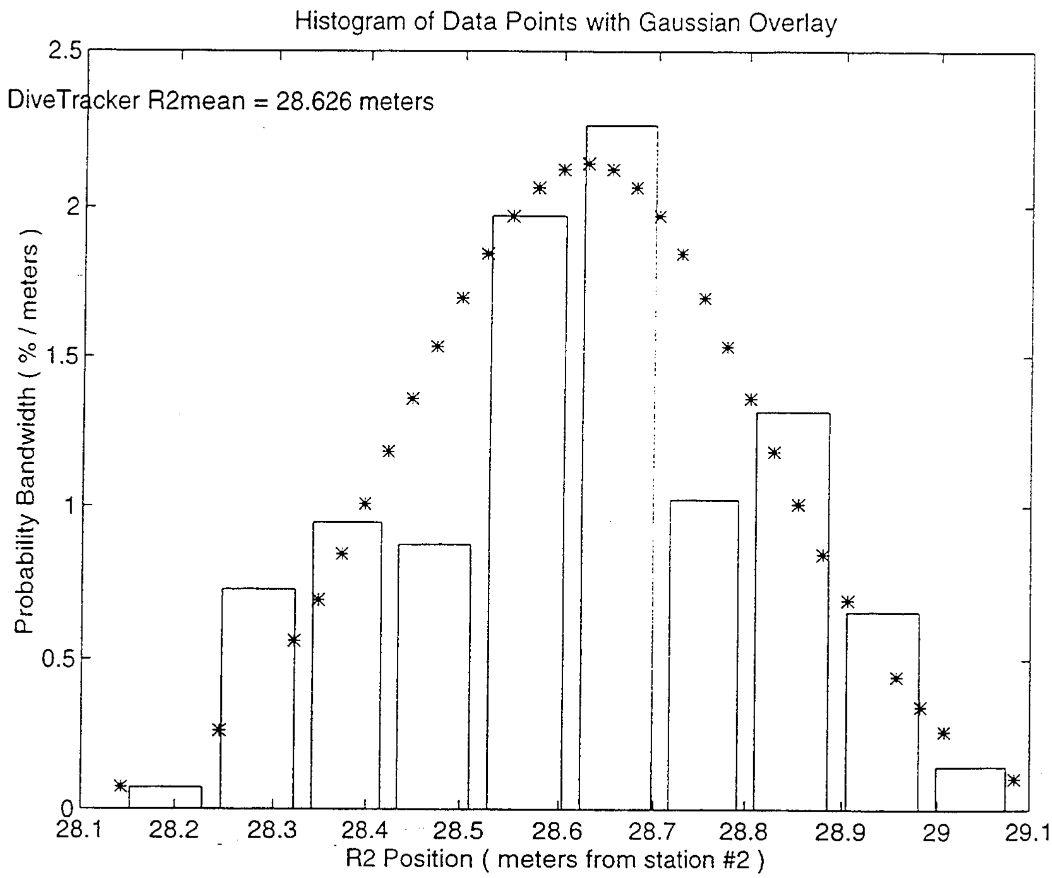


Figure 26. R2 Position Data Histogram for Test #99.

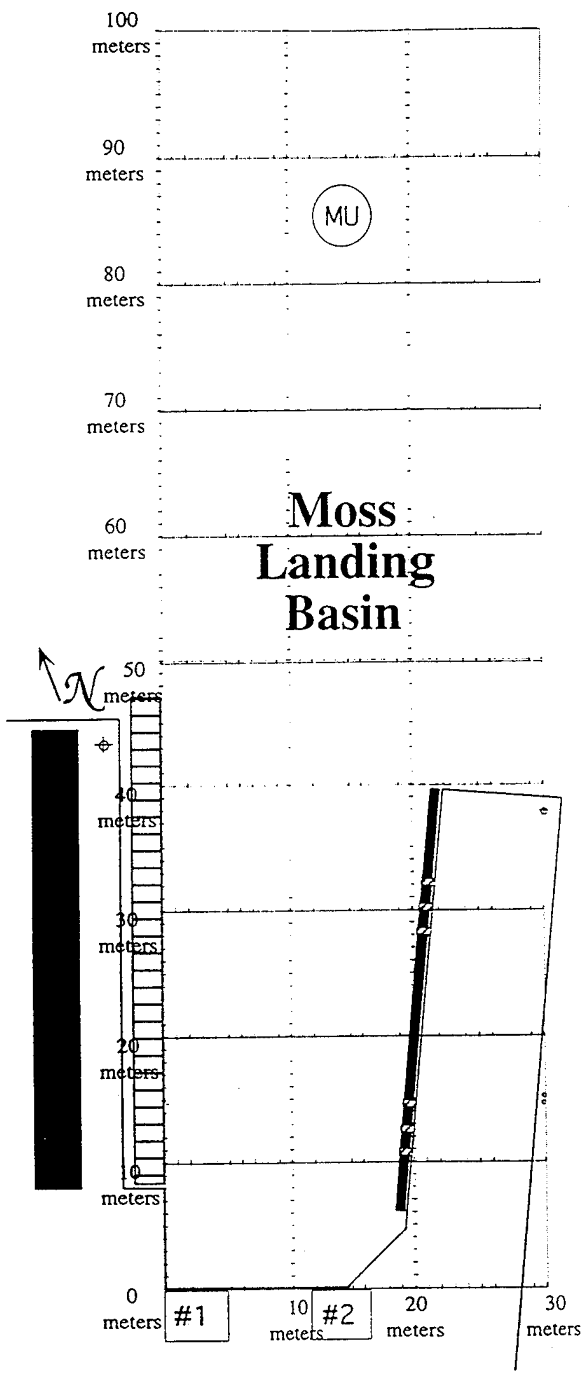


Figure 27. Equipment Set-up for Test #86 at Moss Landing Basin .

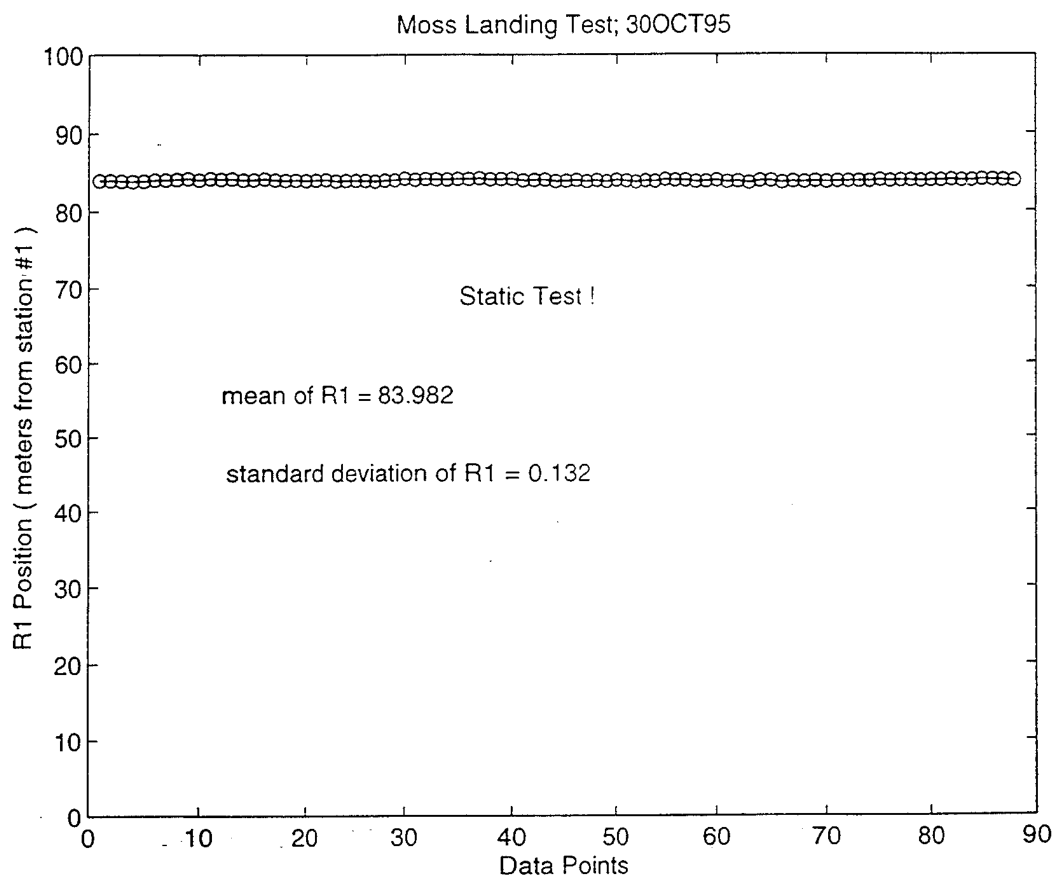


Figure 28. R1 Position Data for Test #86.

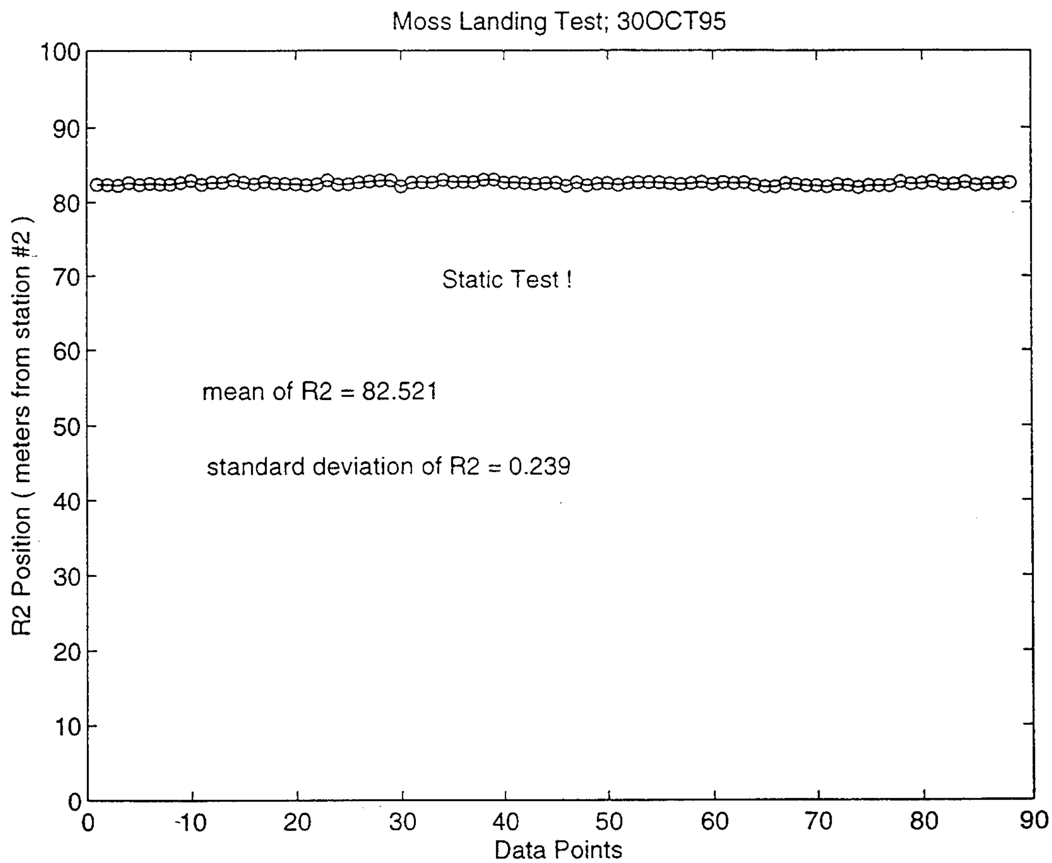


Figure 29. R2 Position Data for Test #86.

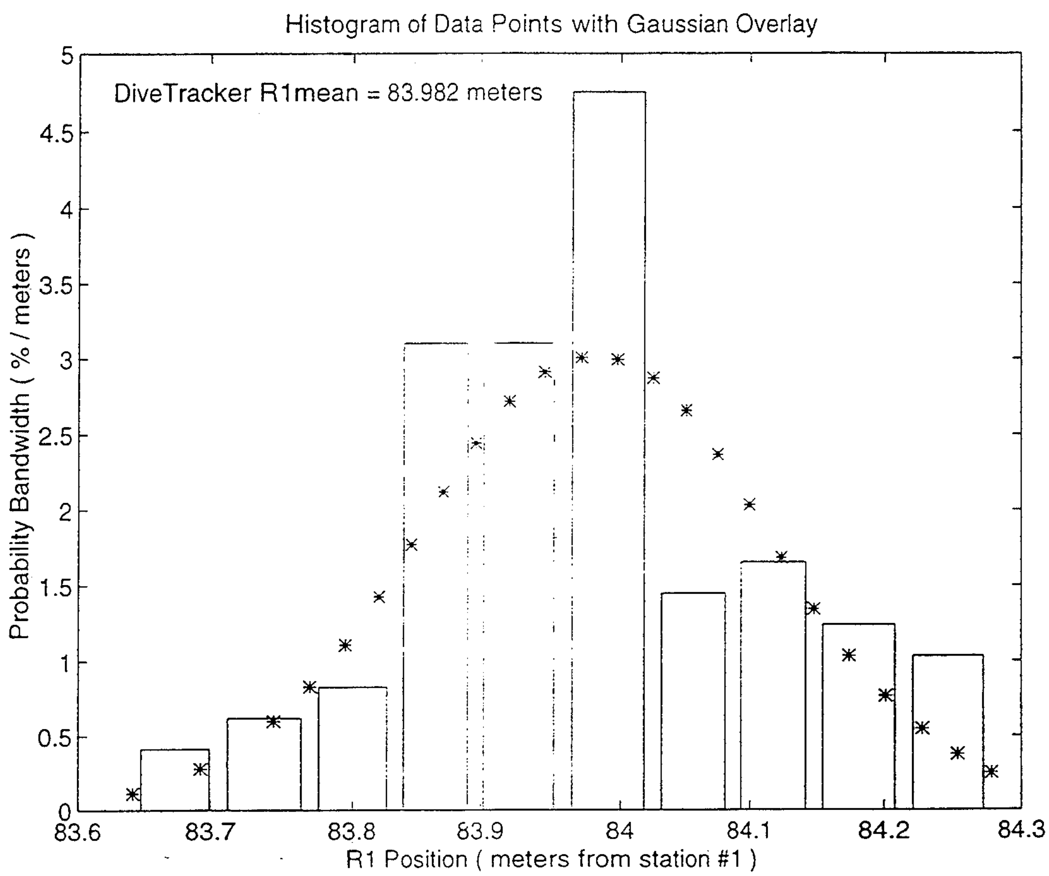


Figure 30. R1 Position Data Histogram for Test #86.

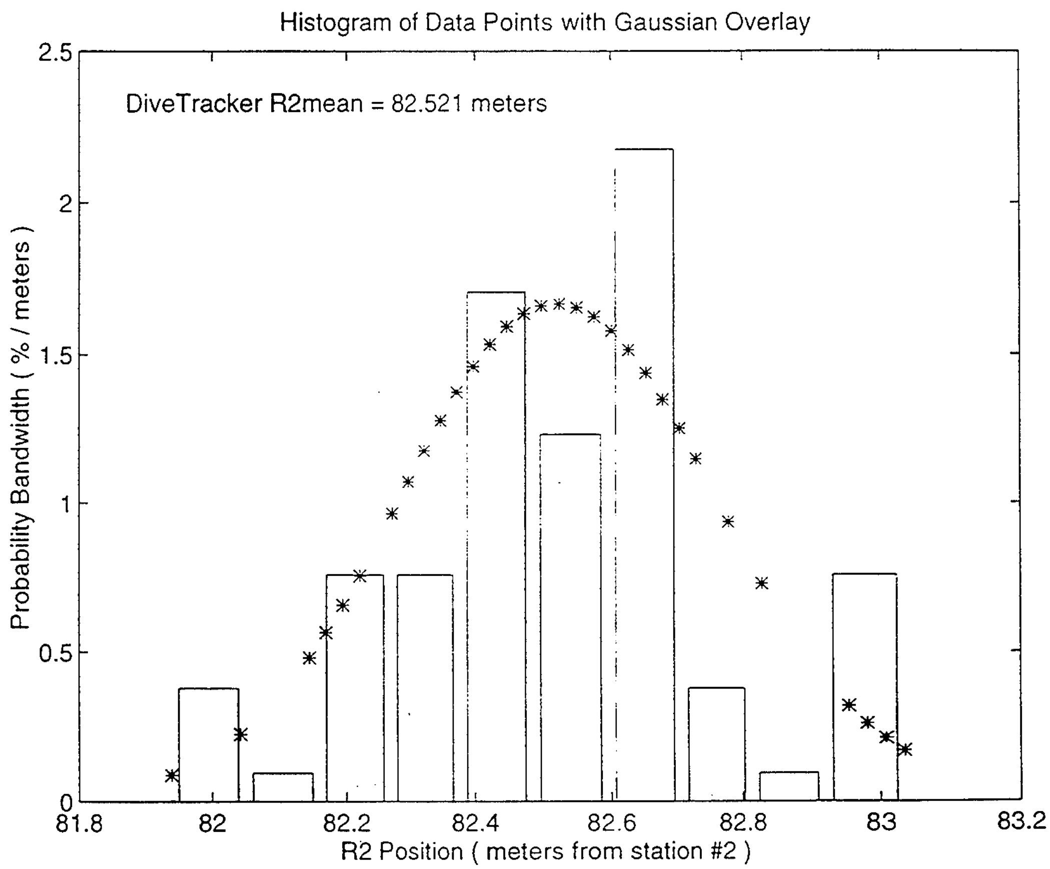


Figure 31. R2 Position Data Histogram for Test #86.

Moss Landing Basin

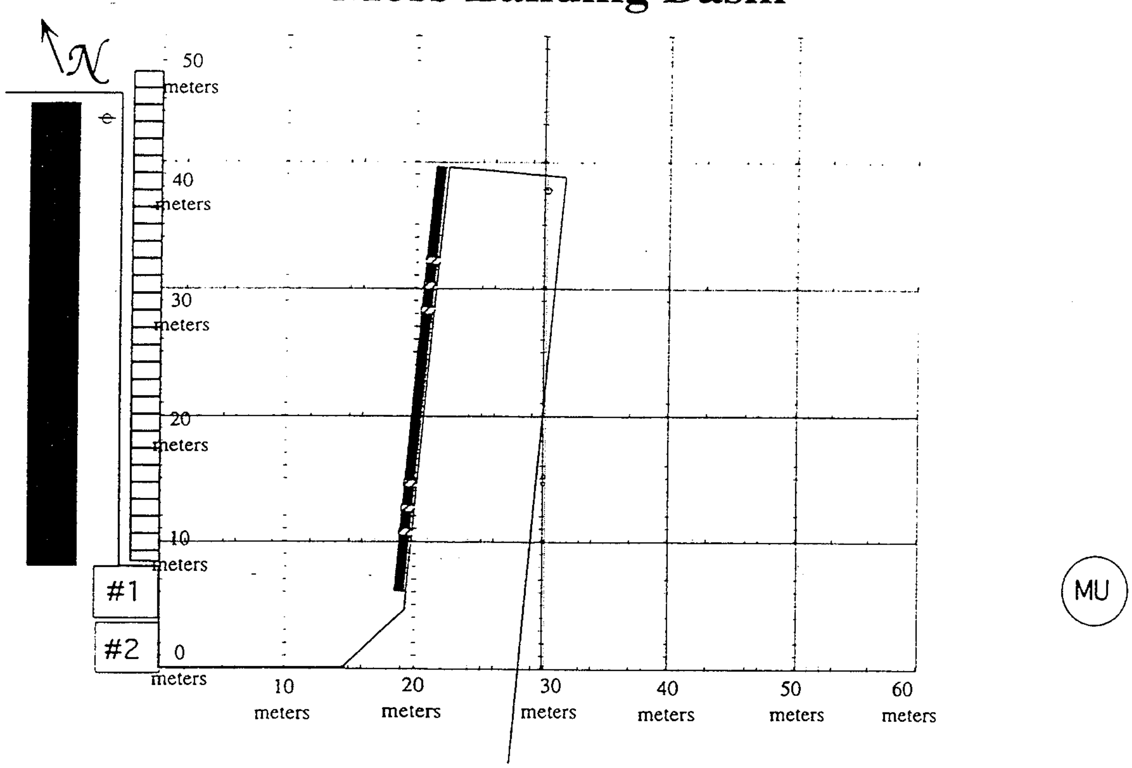


Figure 32. Equipment Set-up for Test #102 at Moss Landing Basin.

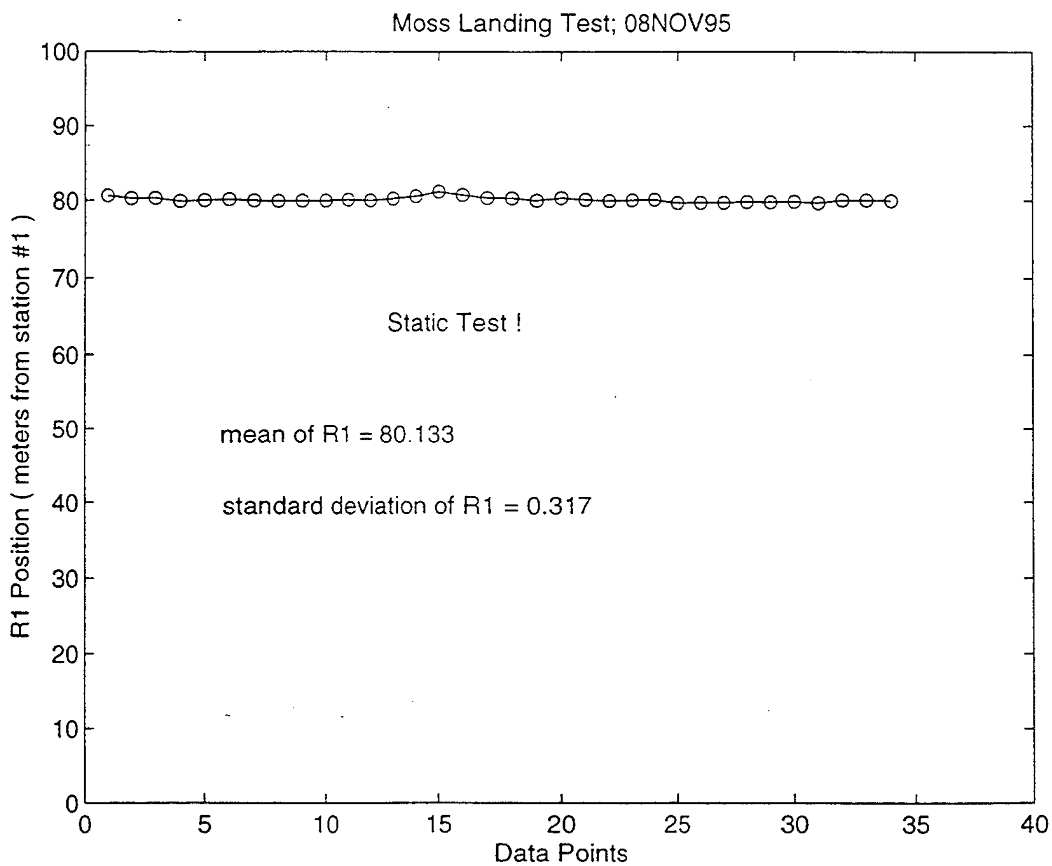


Figure 33. R1 Position Data for Test #102.

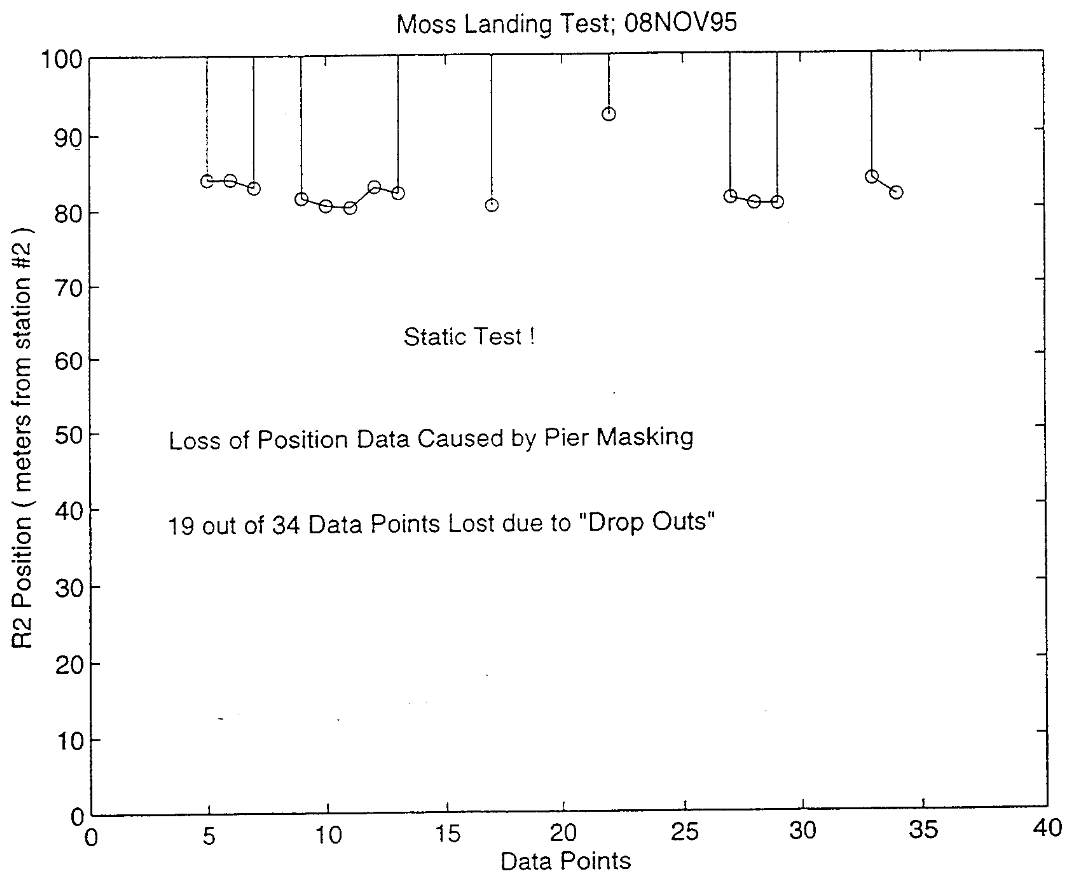


Figure 34. R2 Position Data for Test #102.

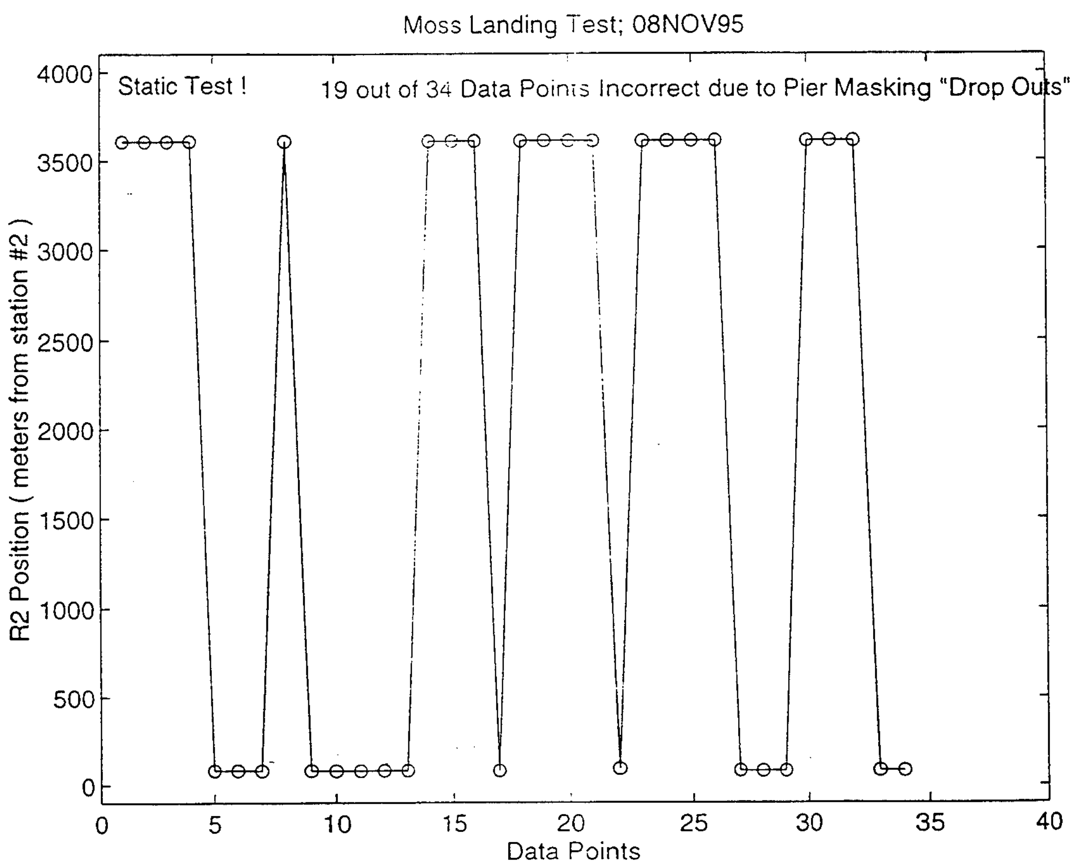


Figure 35. R2 Position Data for Test #102 (re-scaled).

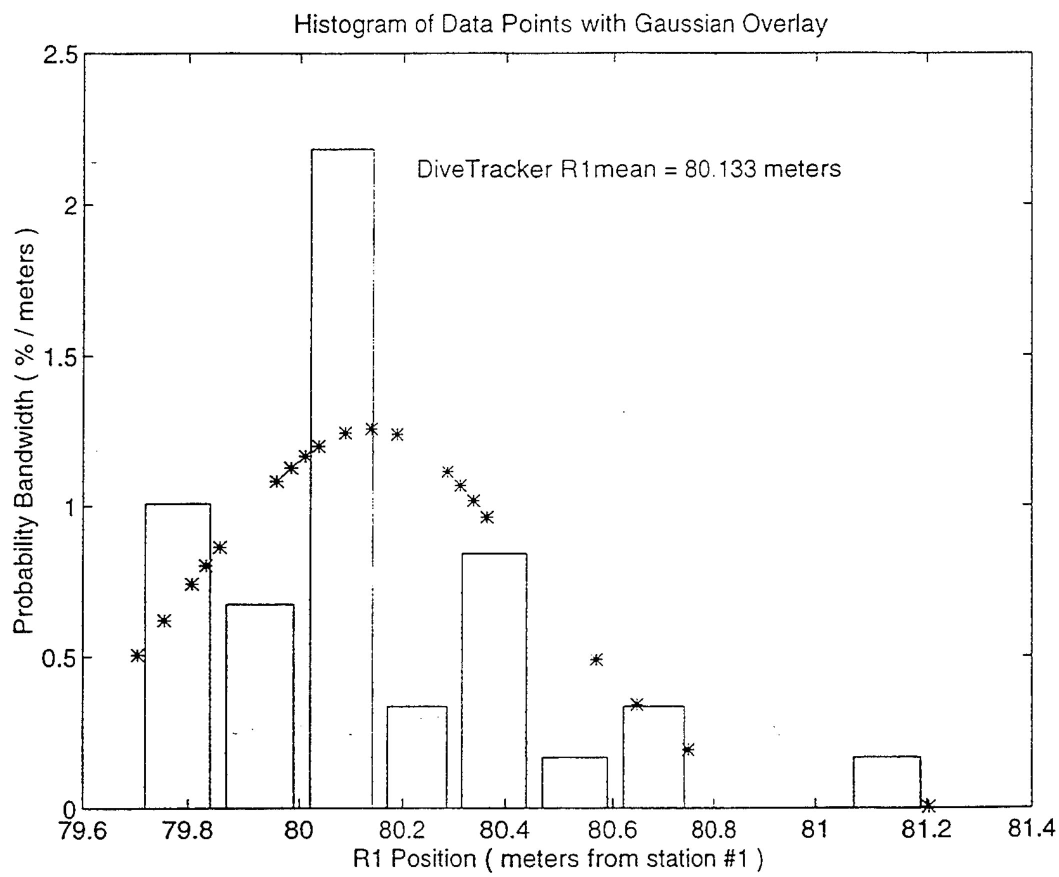


Figure 36. R1 Position Data Histogram for Test #102.

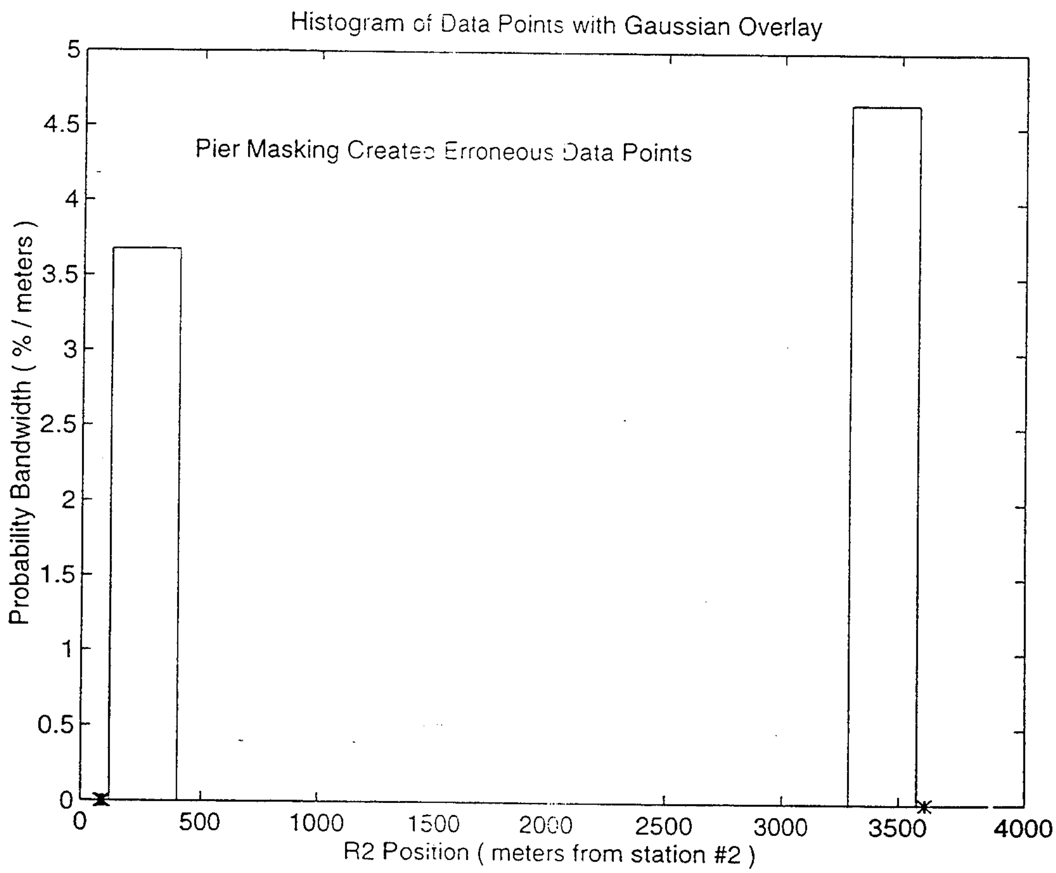


Figure 37. R2 Position Data Histogram for Test #102.

Moss Landing Basin

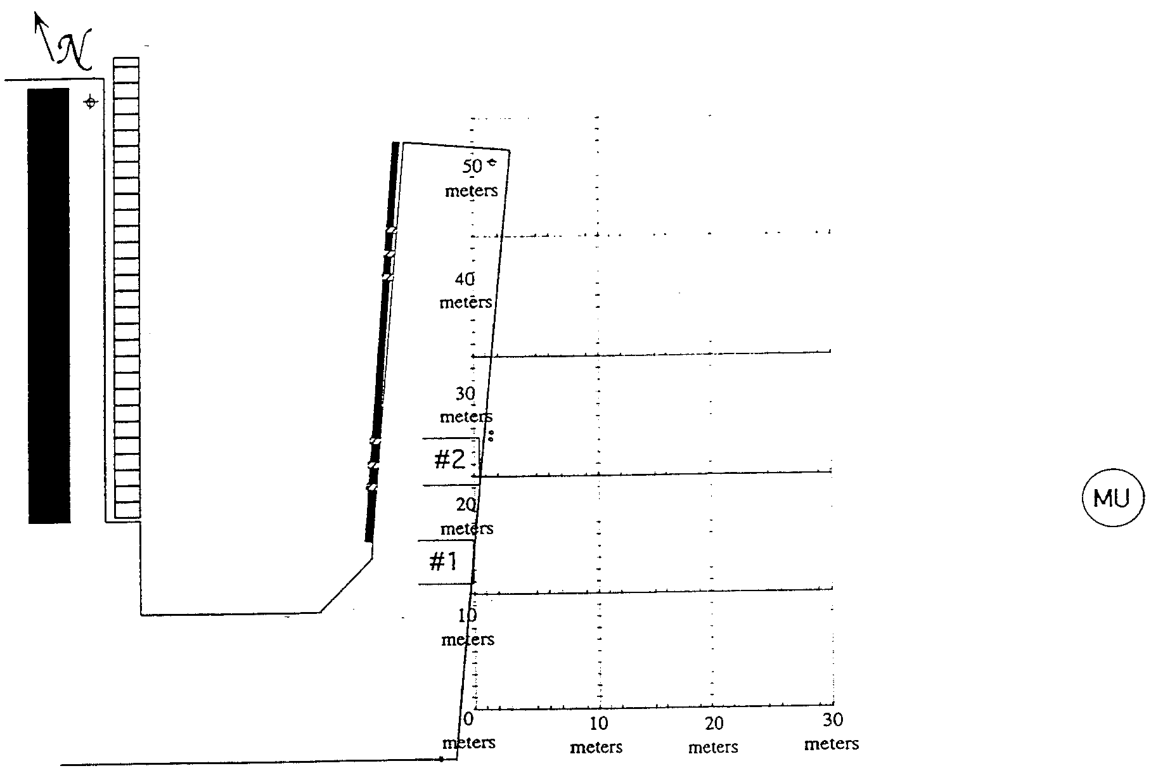


Figure 38. Equipment Set-up for Test #122 at Moss Landing Basin.

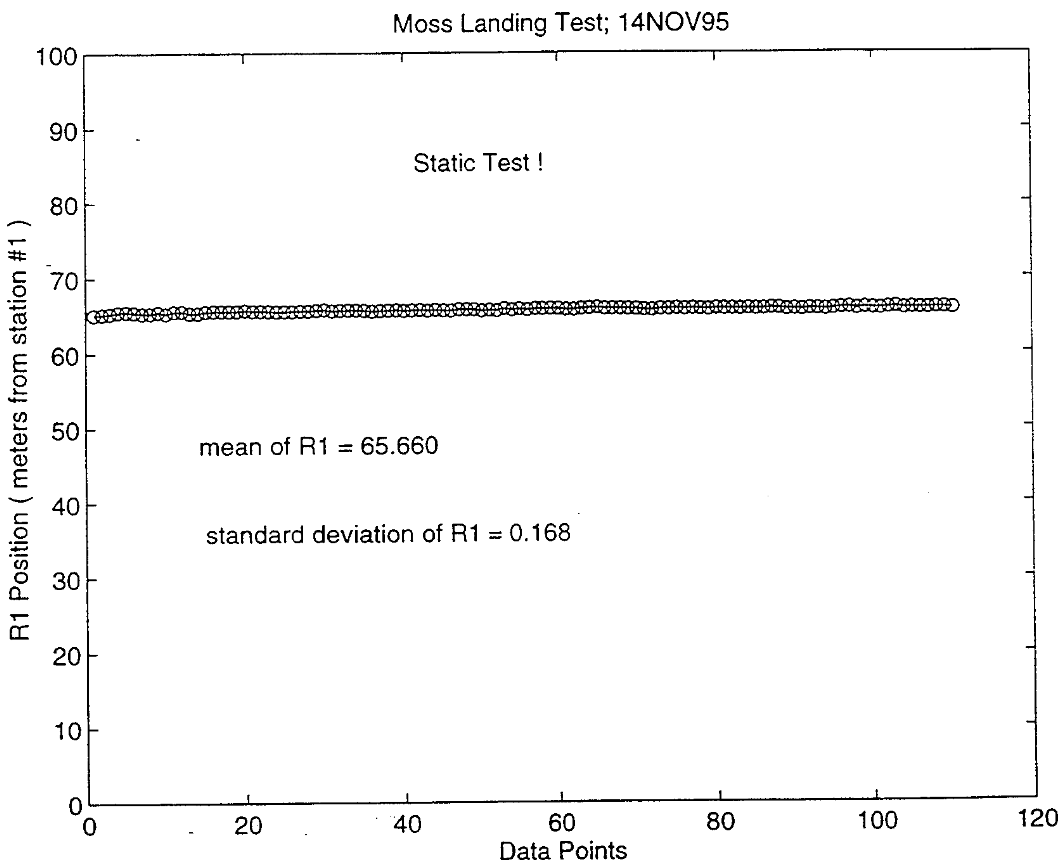


Figure 39. R1 Position Data for Test #122.

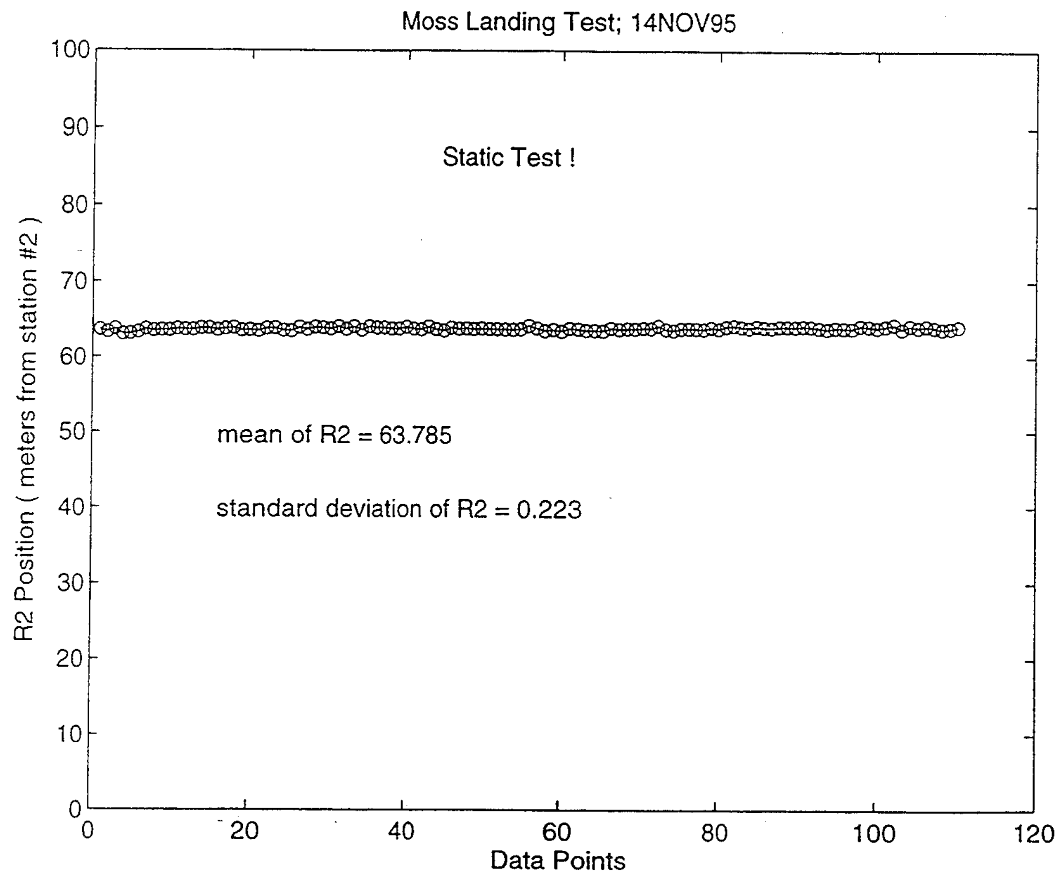


Figure 40. R2 Position Data for Test #122.

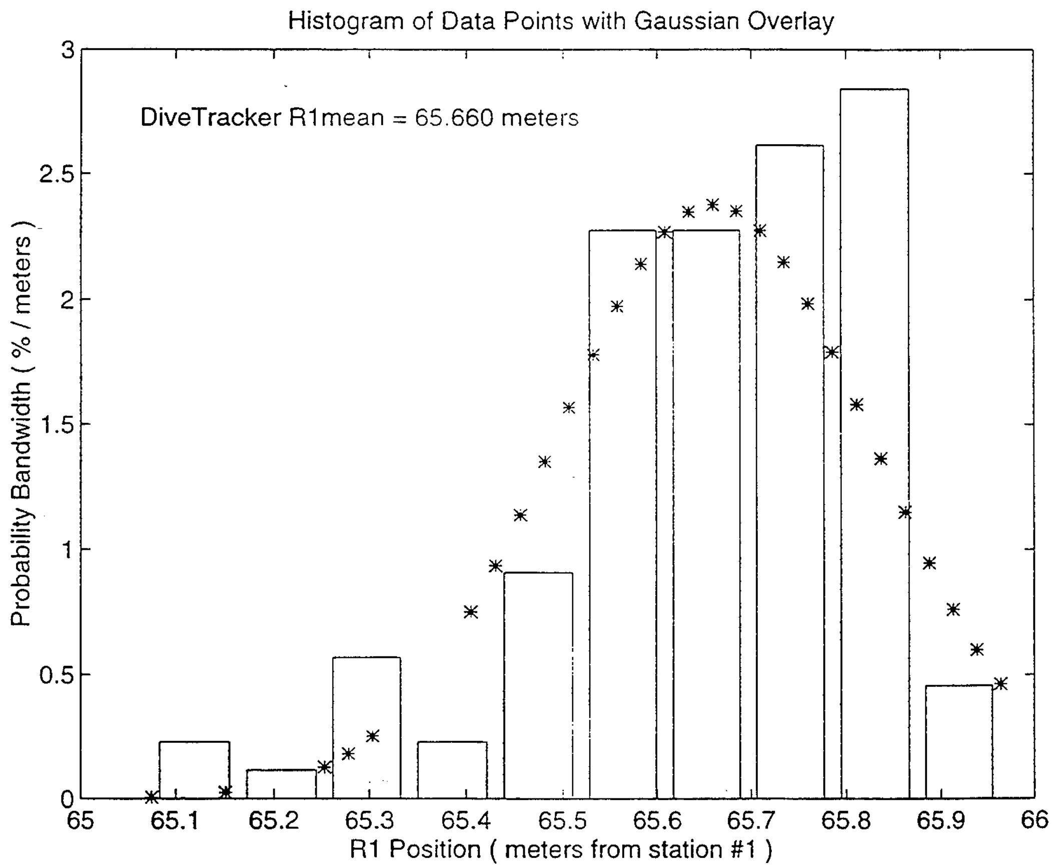


Figure 41. R1 Position Data Histogram for Test #122.

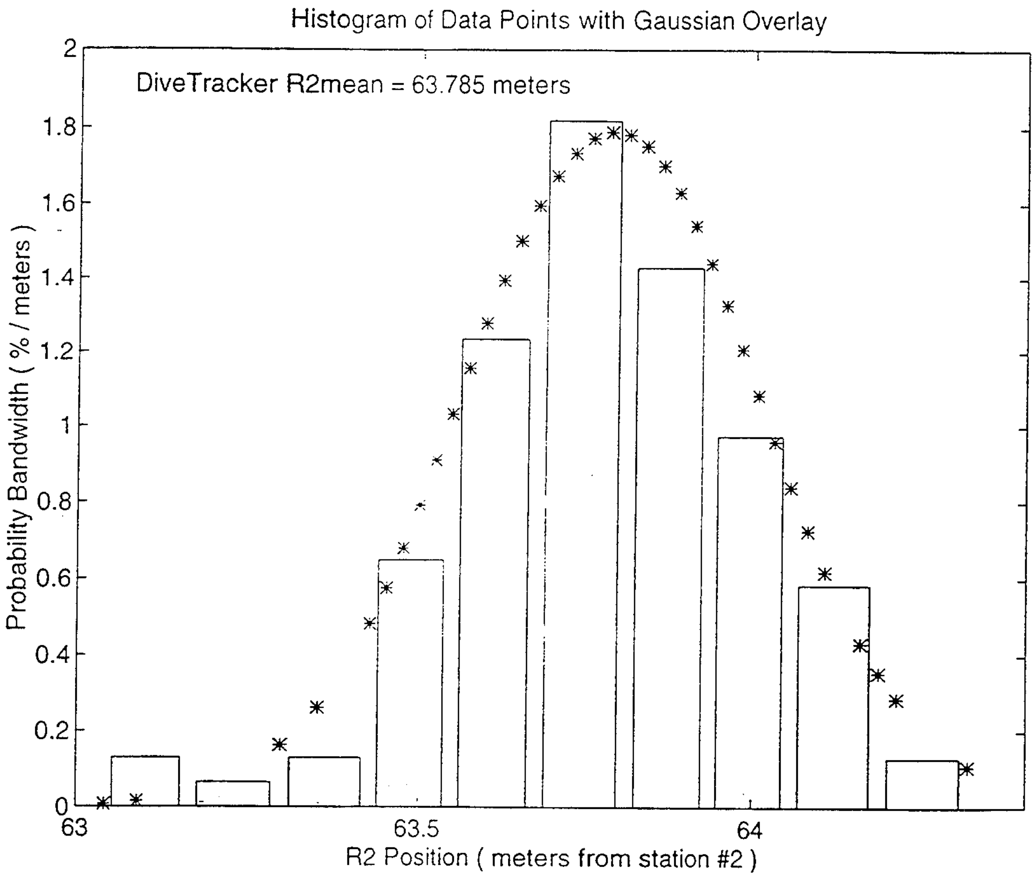


Figure 42. R2 Position Data Histogram for Test #122.

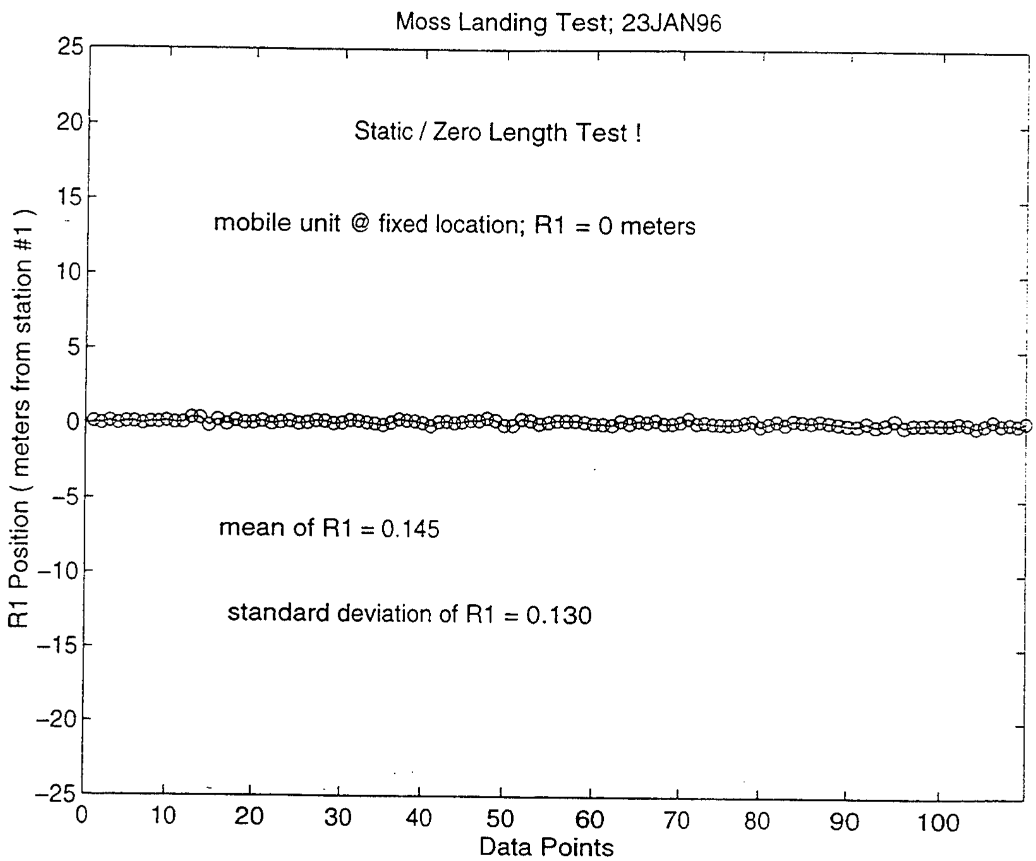


Figure 43. R1 Position Data for Test #150.

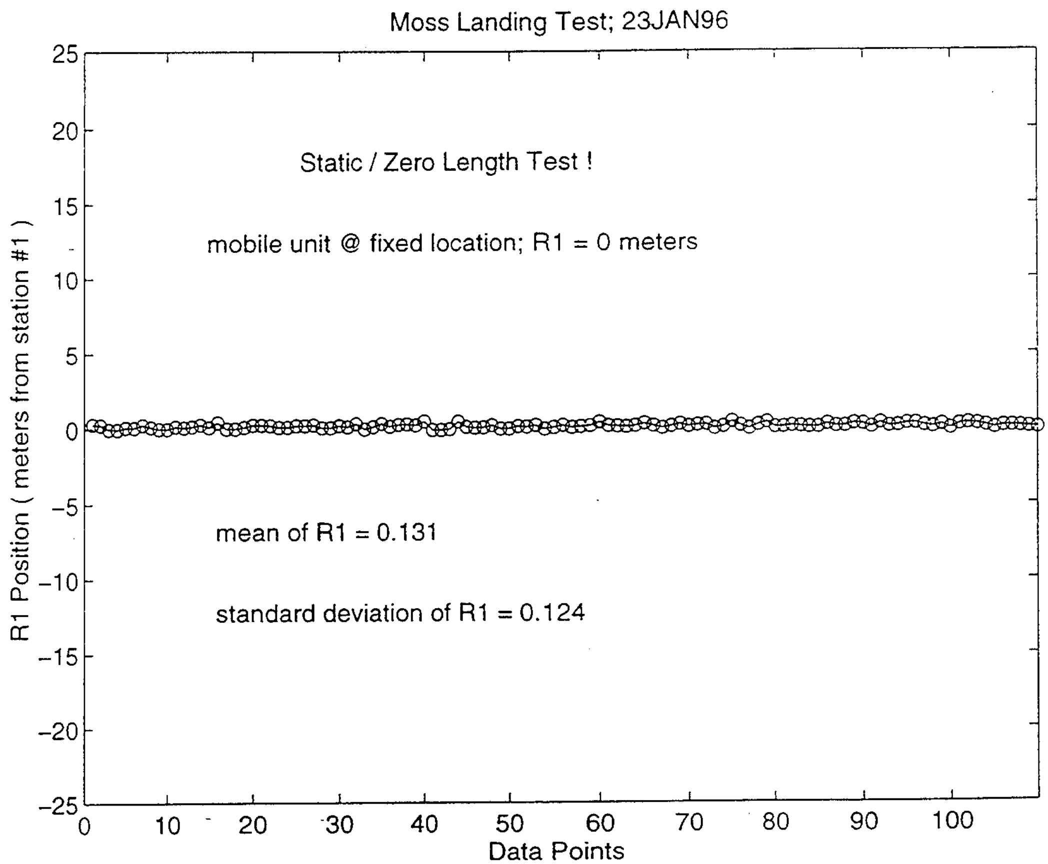


Figure 44. R1 Position Data for Test #151.

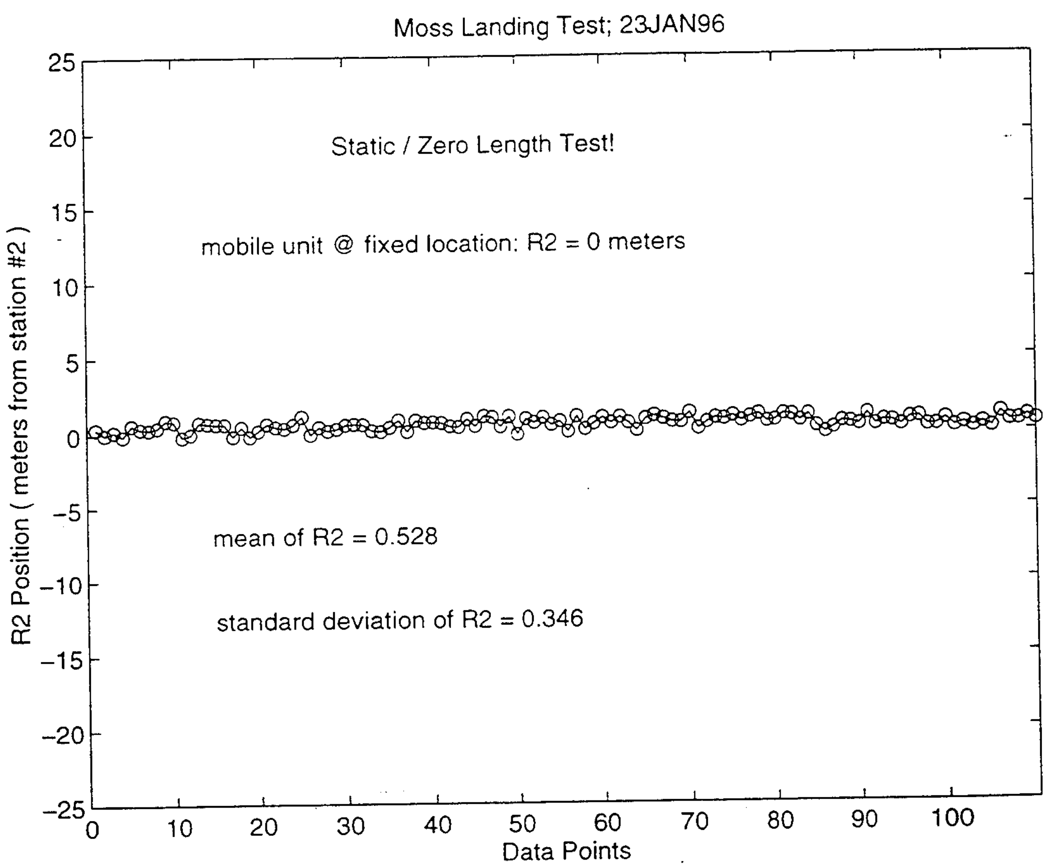


Figure 45. R2 Position Data for Test #152.

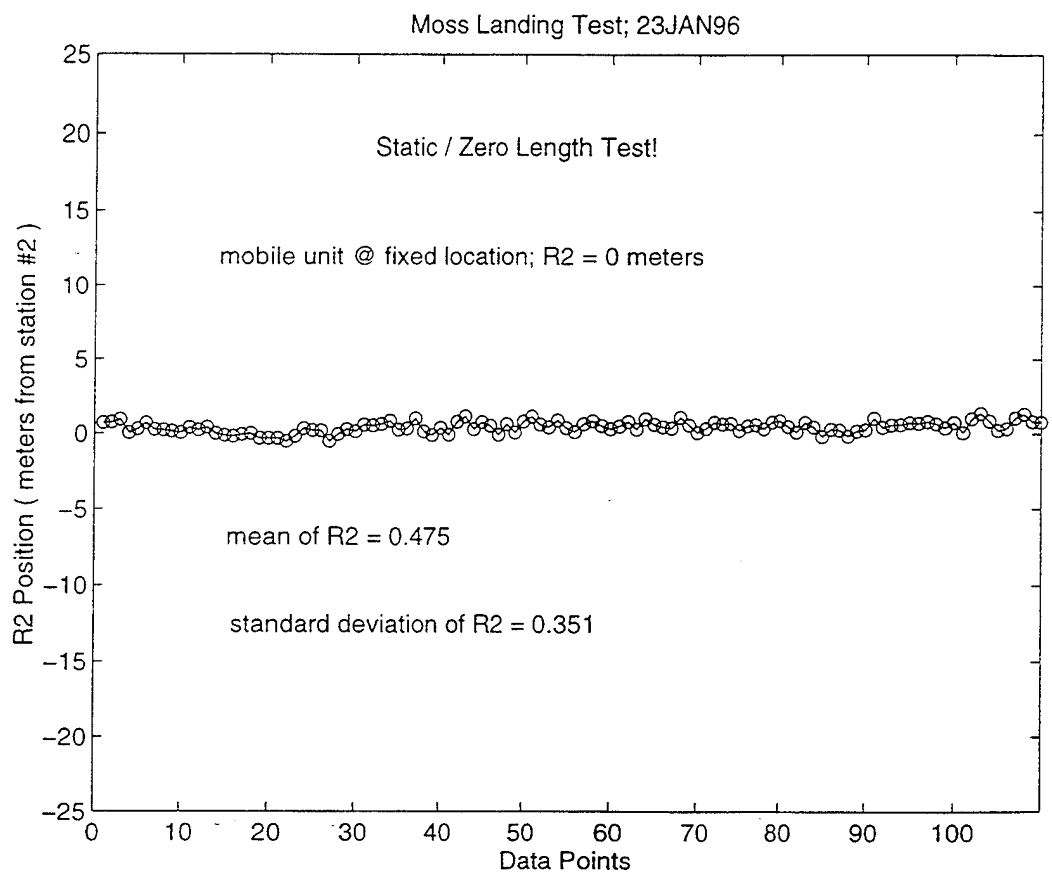


Figure 46. R2 Position Data for Test #153.

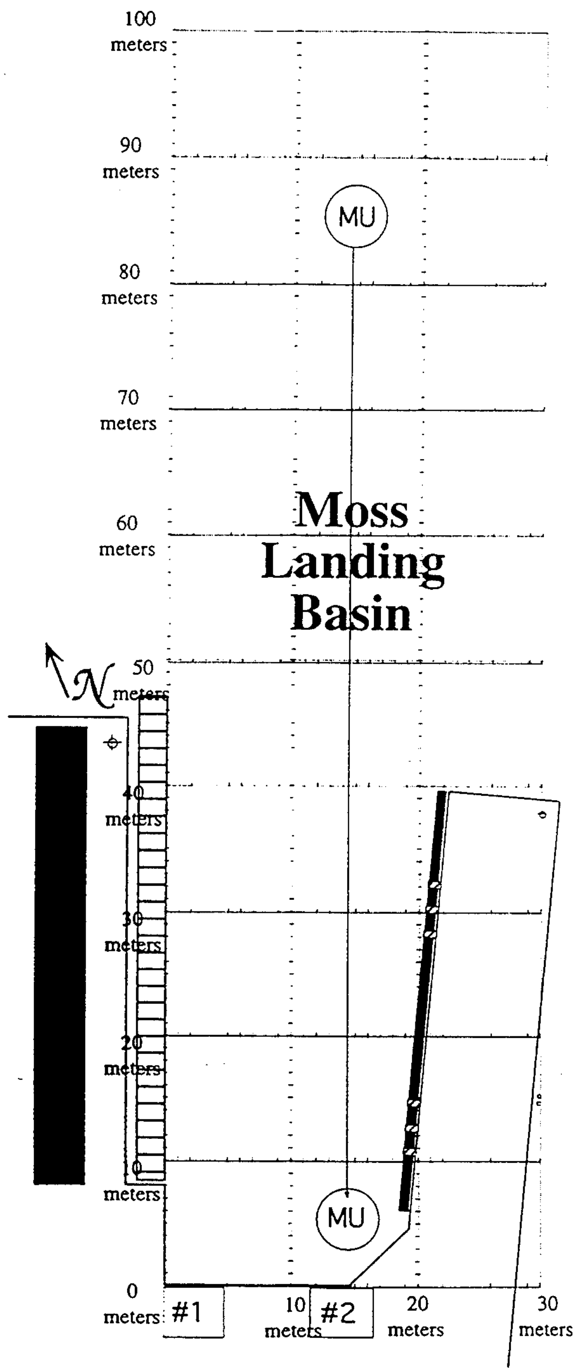


Figure 47. Equipment Set-up for Test # 87 at Moss Landing Basin.

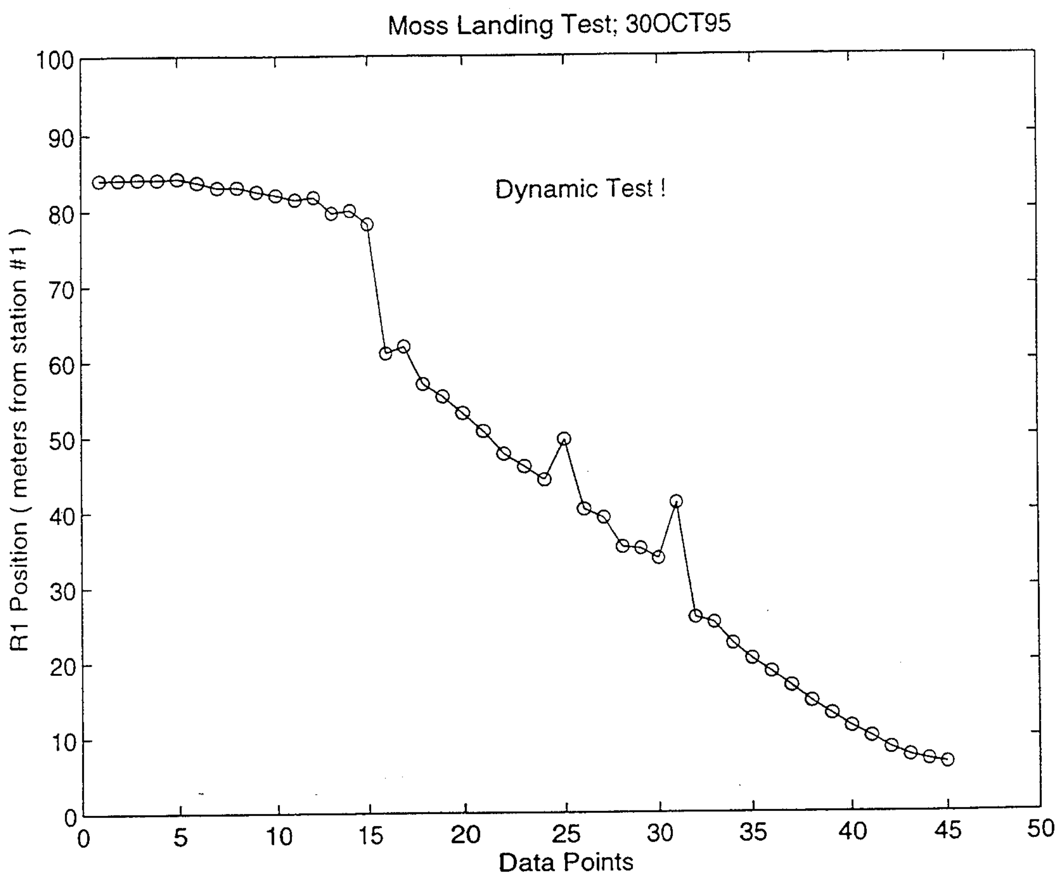


Figure 48. R1 Position Data for Test #87.

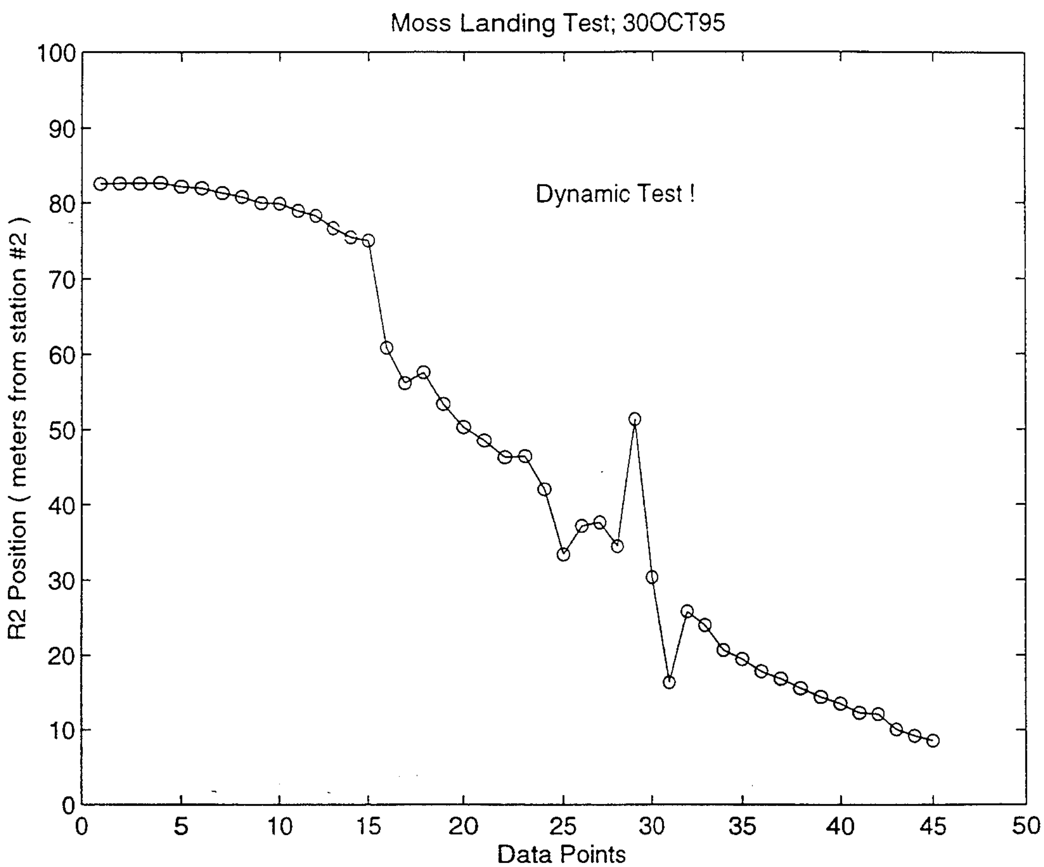


Figure 49. R2 Position Data for Test #87.

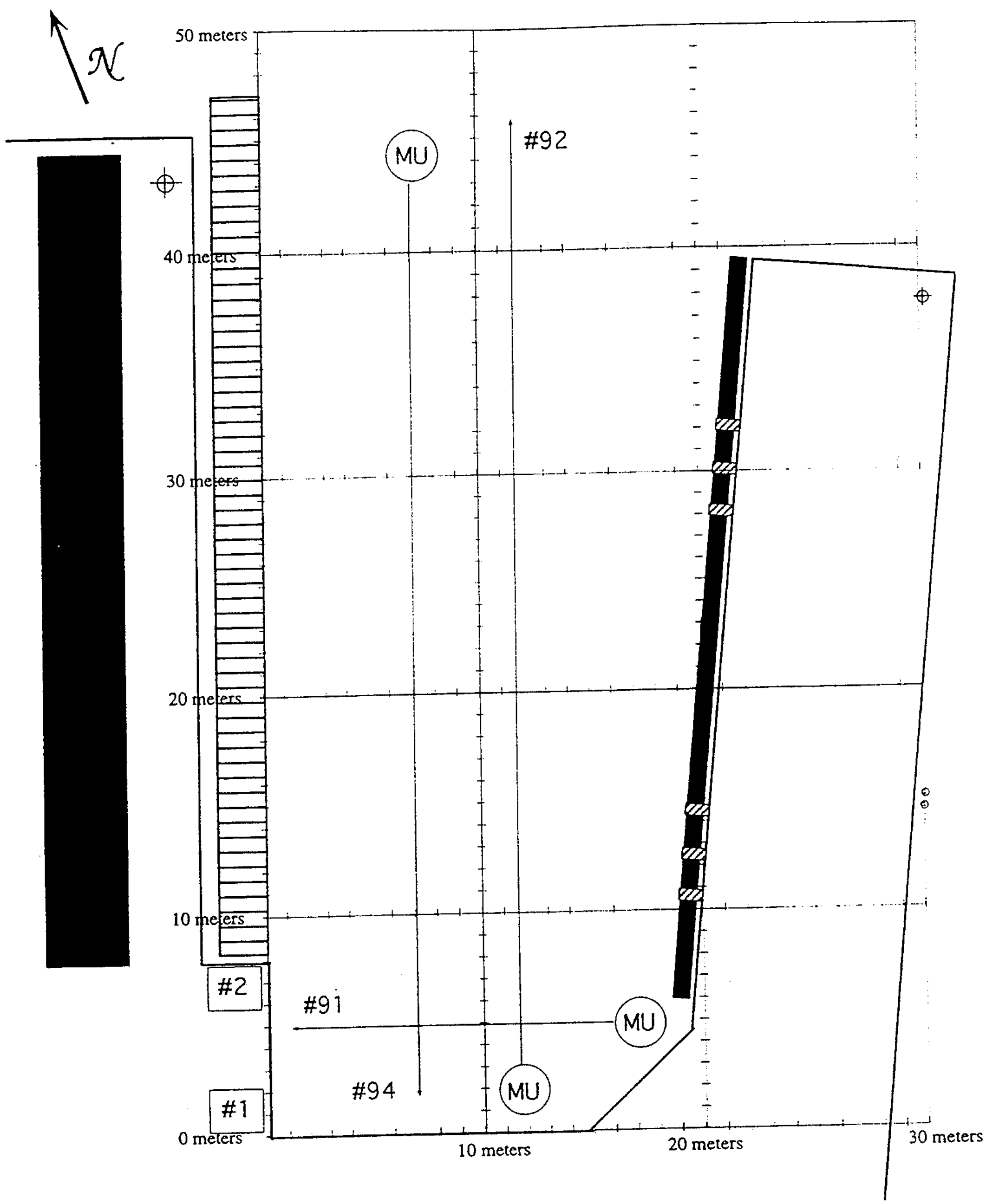


Figure 50. Equipment Set-up for Tests #91, #92, and #94 at Moss Landing Basin.

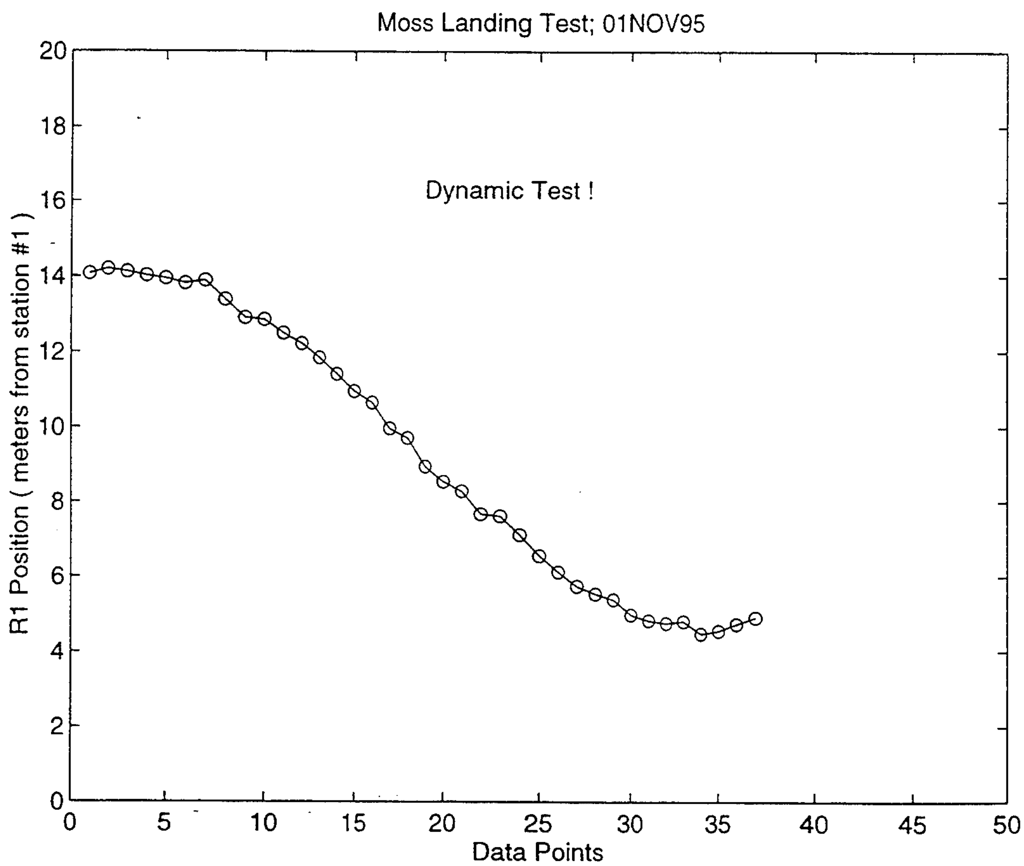


Figure 51. R1 Position Data for Test #91.

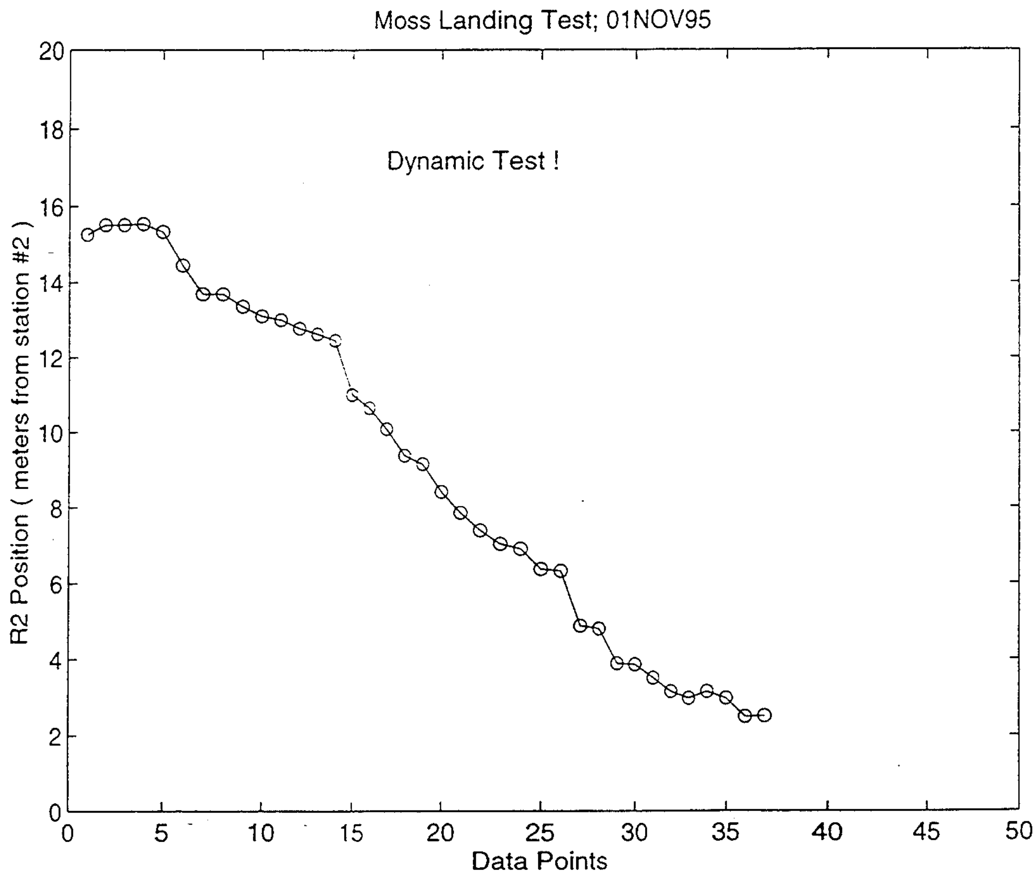


Figure 52. R2 Position Data for Test #91.

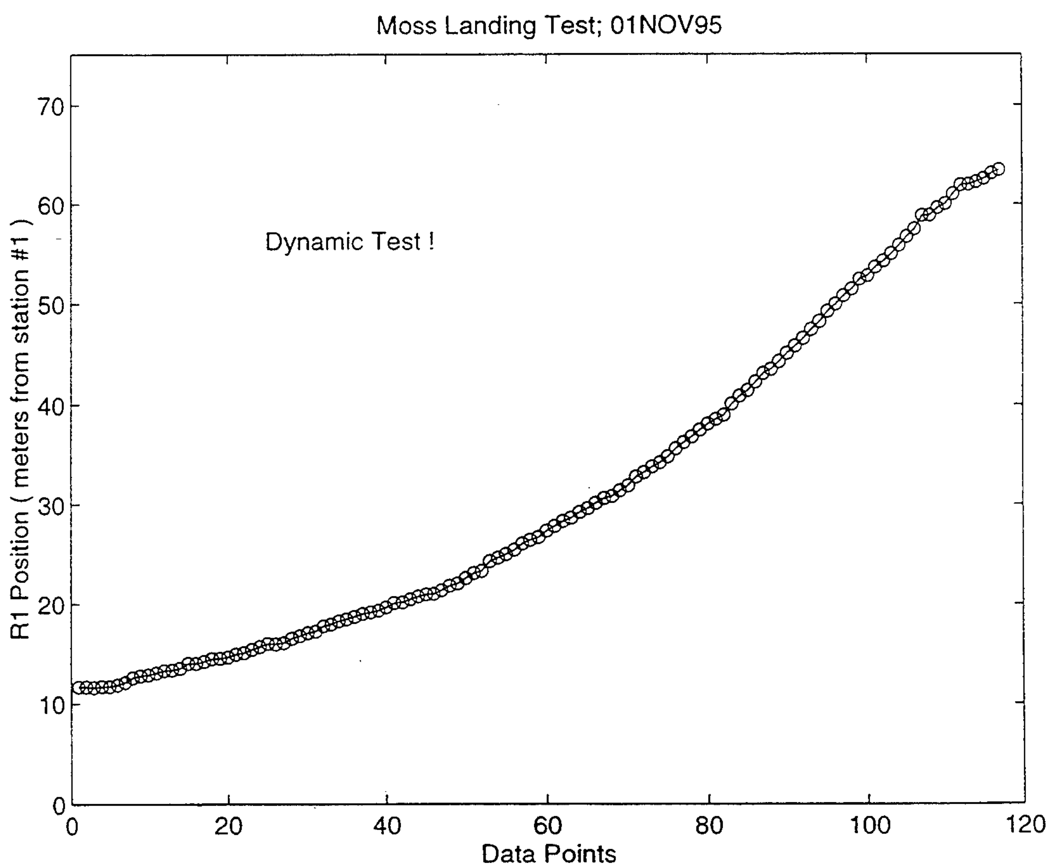


Figure 53. R1 Position Data for Test #92.

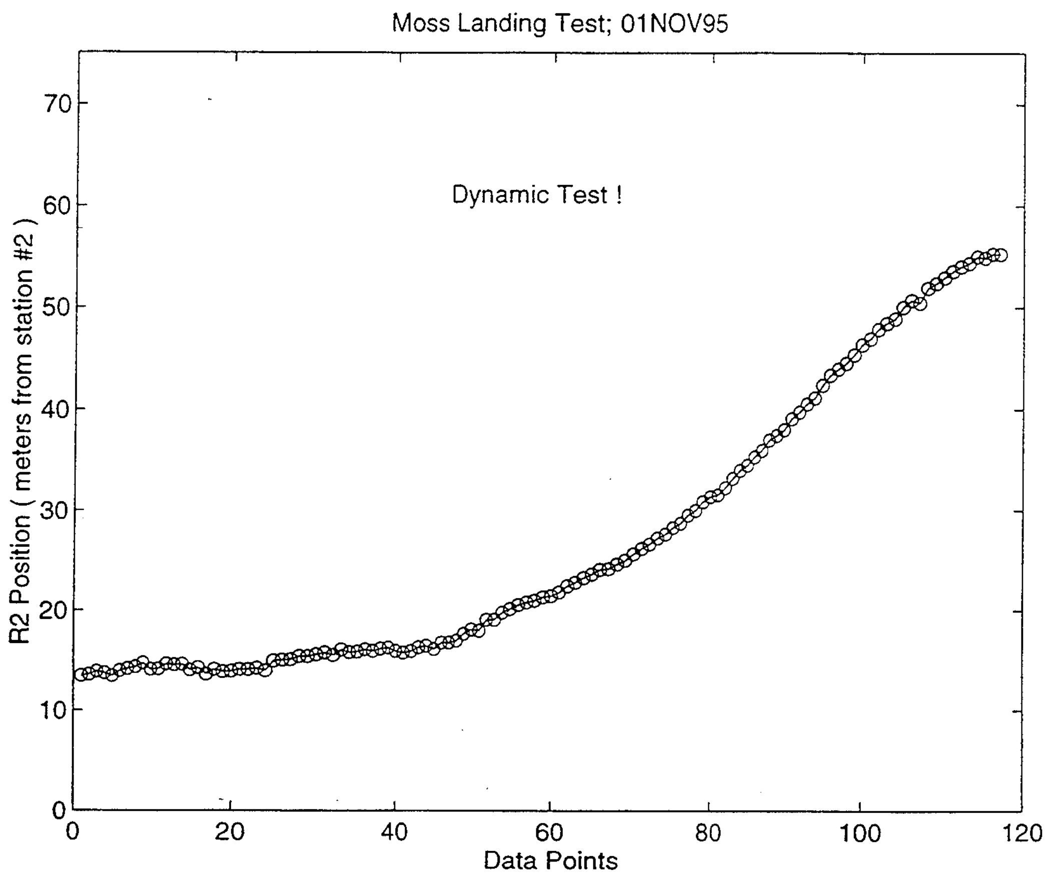


Figure 54. R2 Position Data for Test #92.

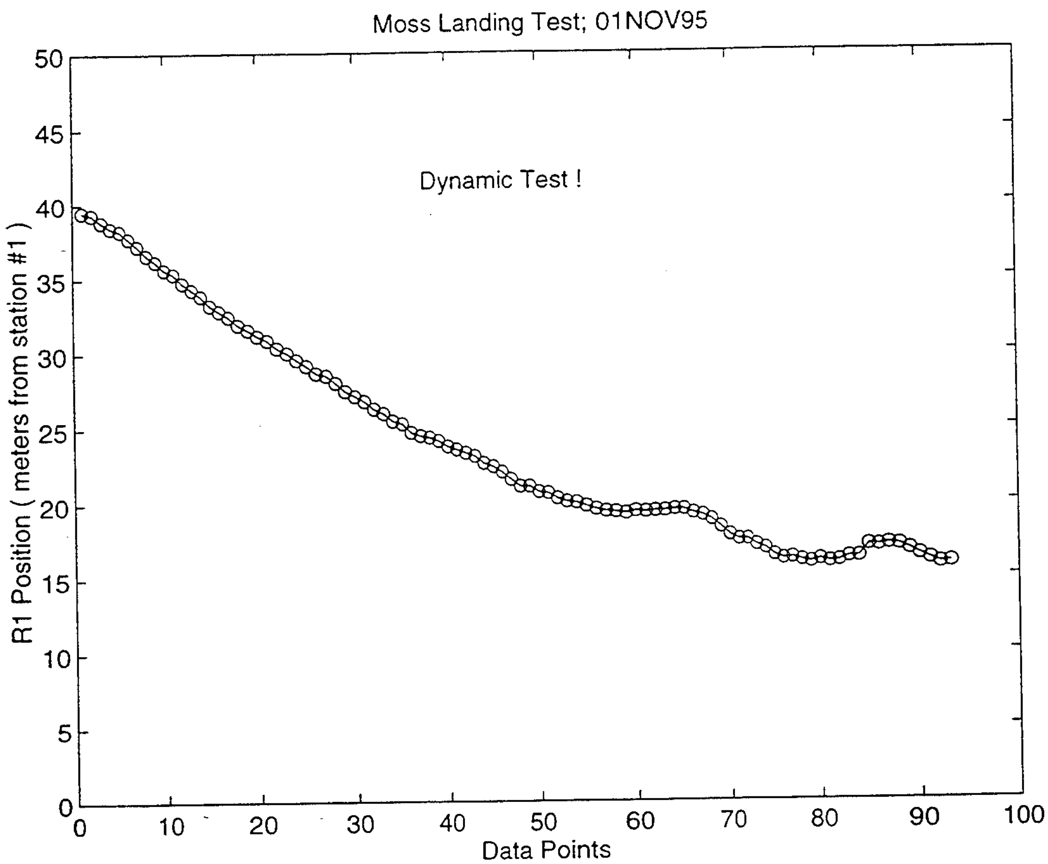


Figure 55. R1 Position Data for Test #94.

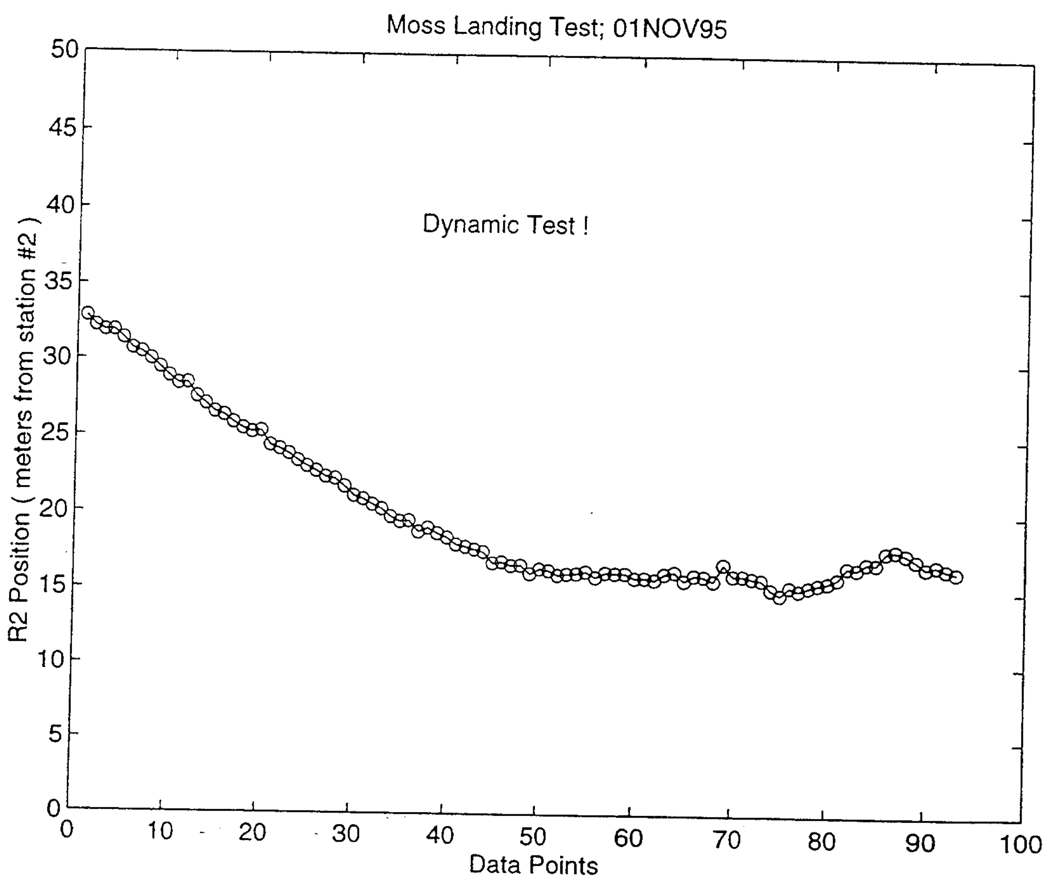


Figure 56. R2 Position Data for Test #94.

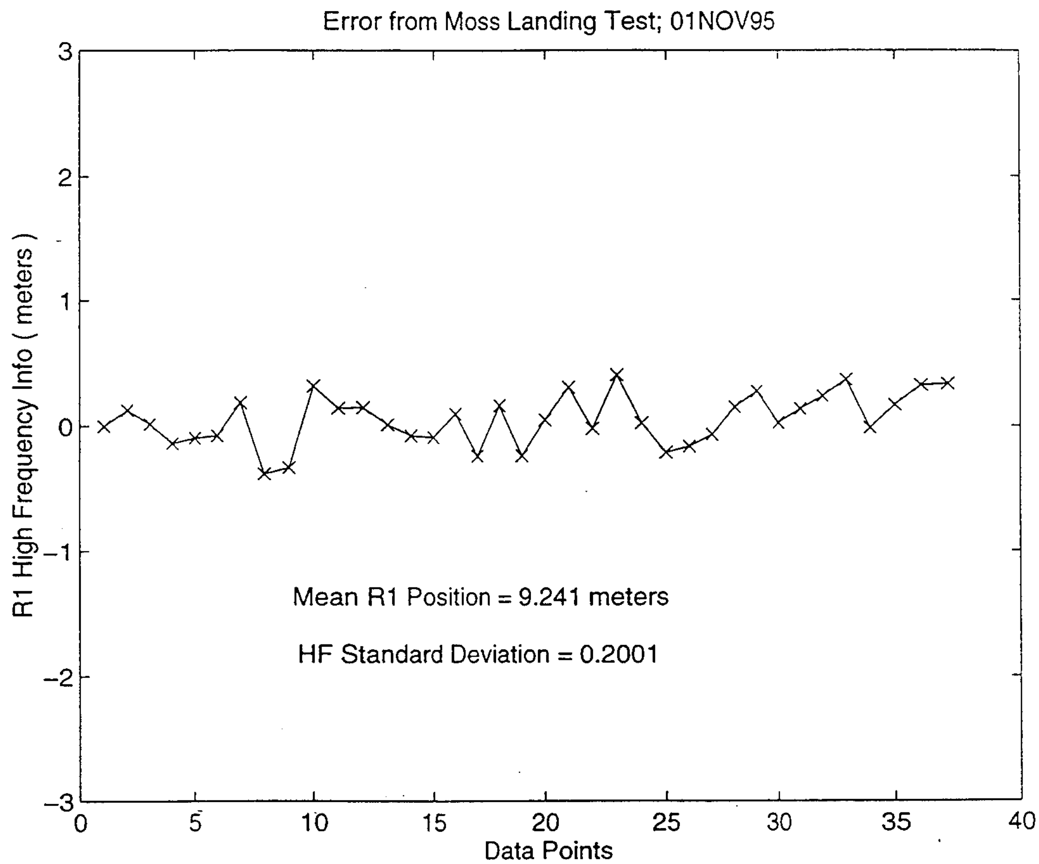


Figure 57. R1 High Frequency Data for Test #91.

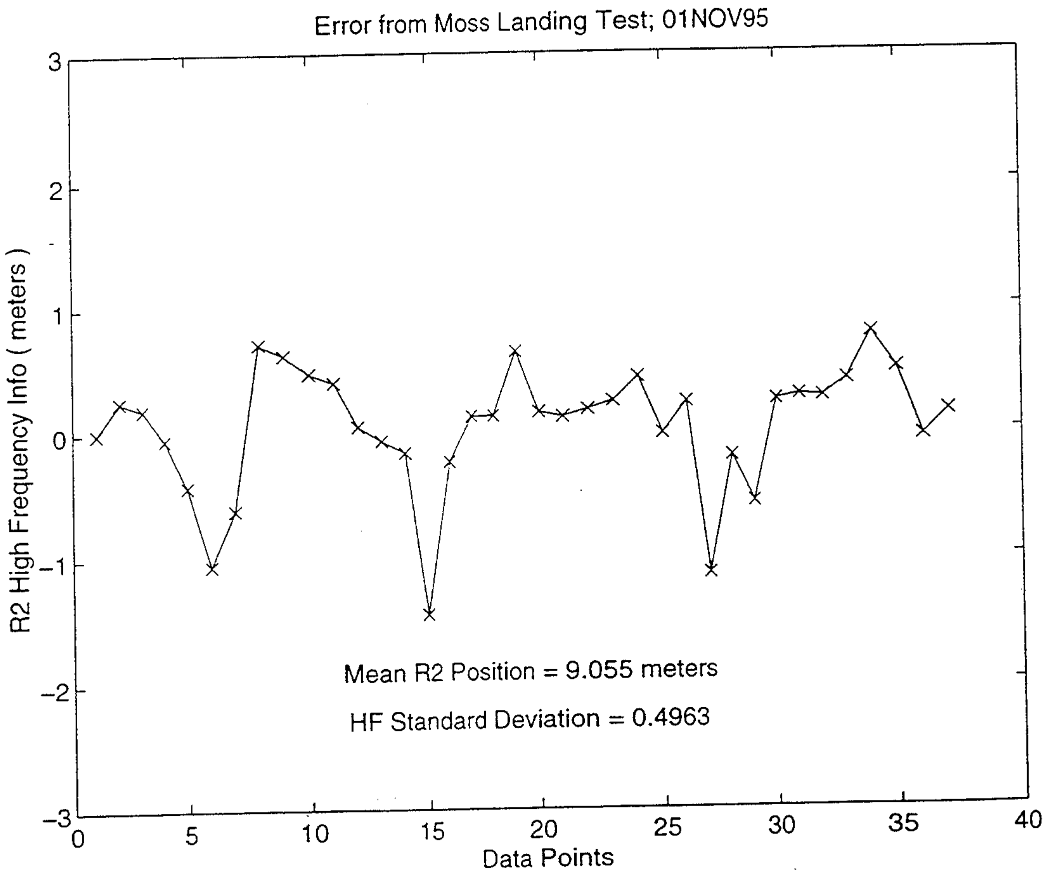


Figure 58. R2 High Frequency Data for Test #91.

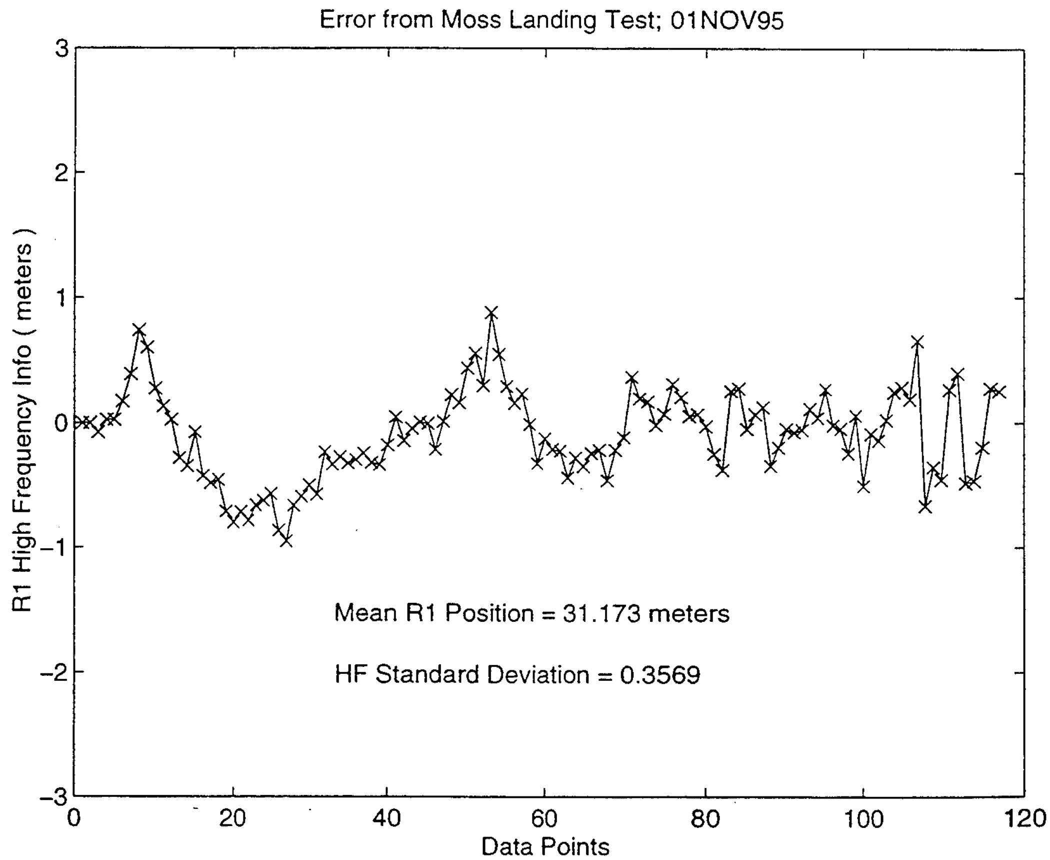


Figure 59. R1 High Frequency Data for Test #92.

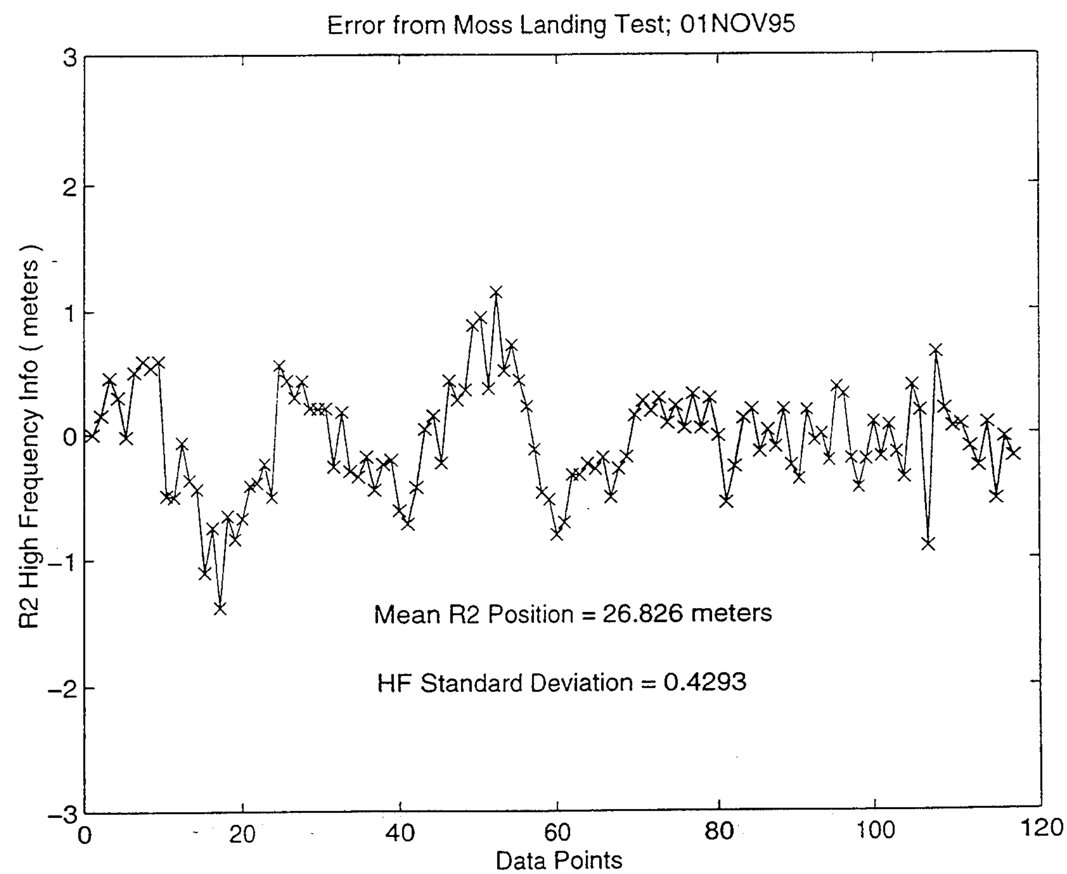


Figure 60. R2 High Frequency Data for Test #92.

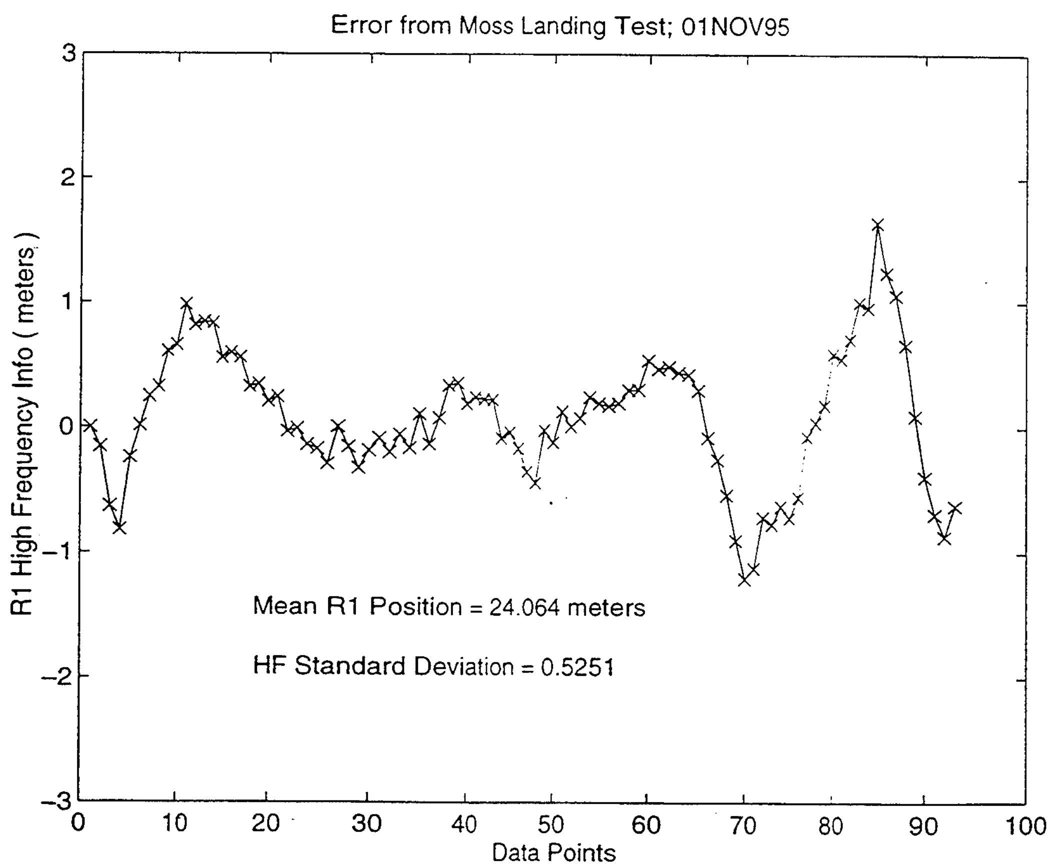


Figure 61. R1 High Frequency Data for Test #94.

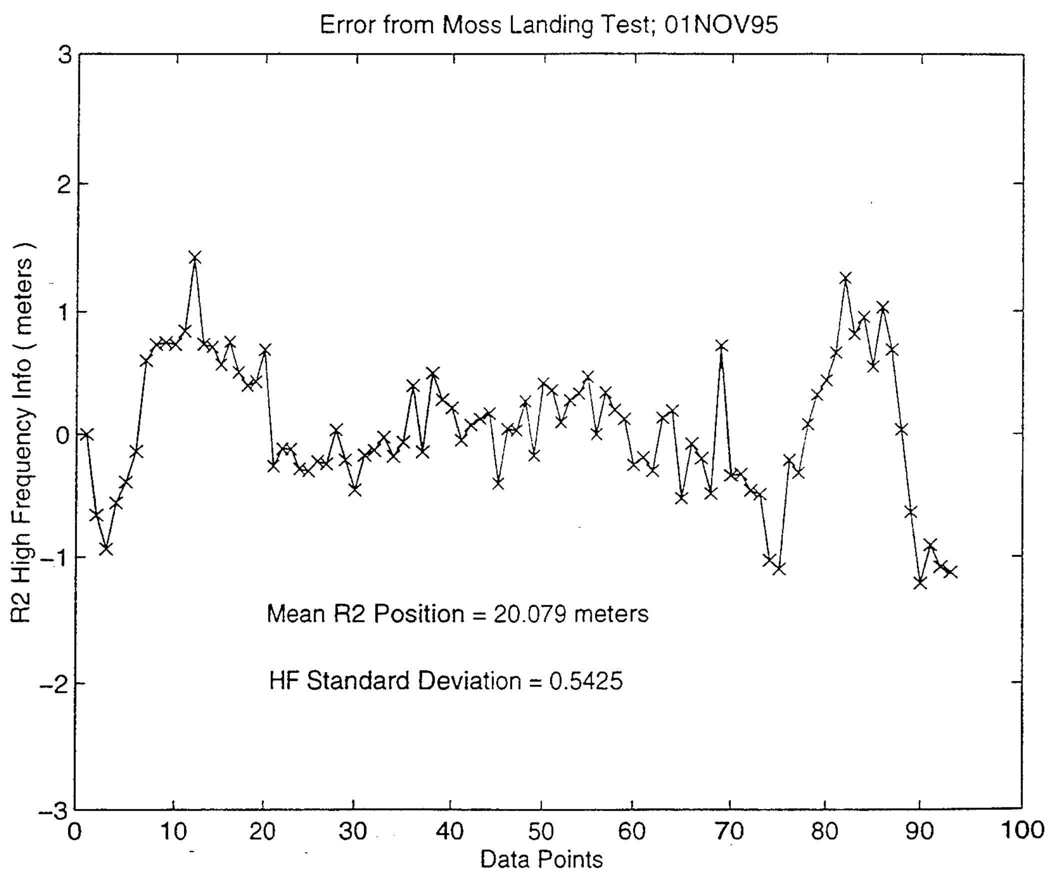


Figure 62. R2 High Frequency Data for Test #94.

Moss Landing Basin

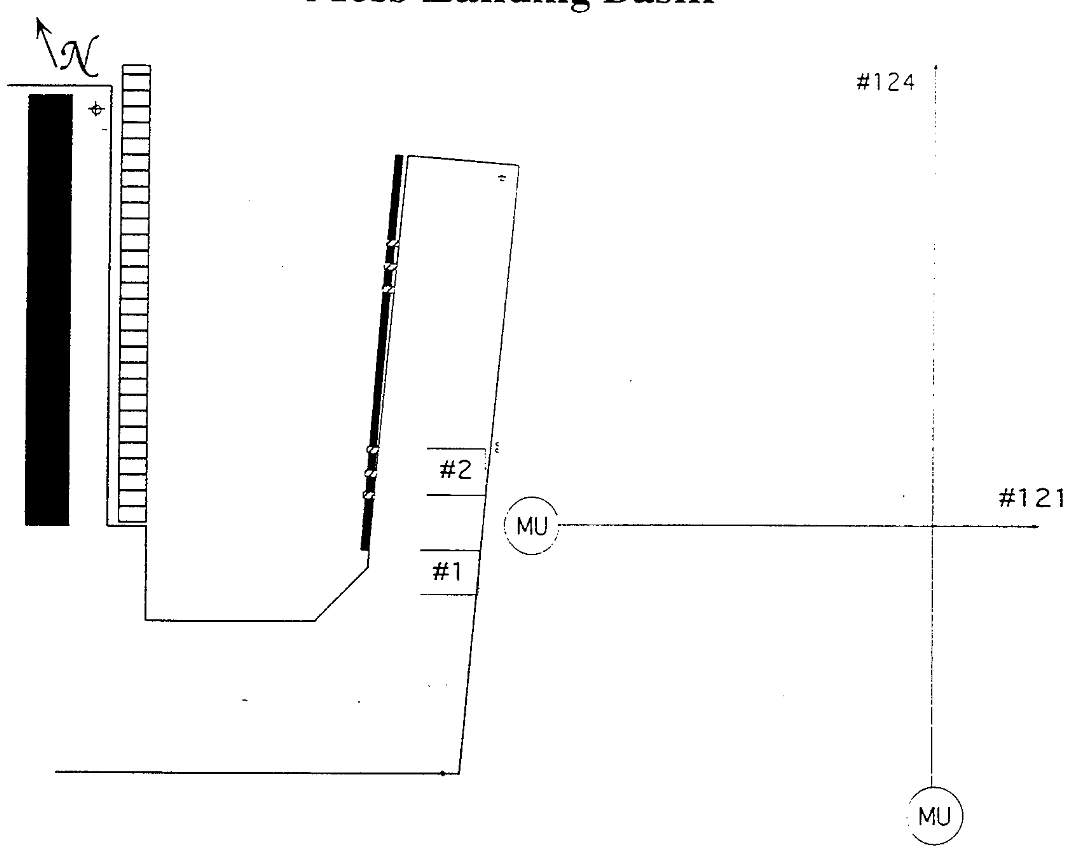


Figure 63. Equipment Set-up for Tests #121 and #124 at Moss Landing Basin.

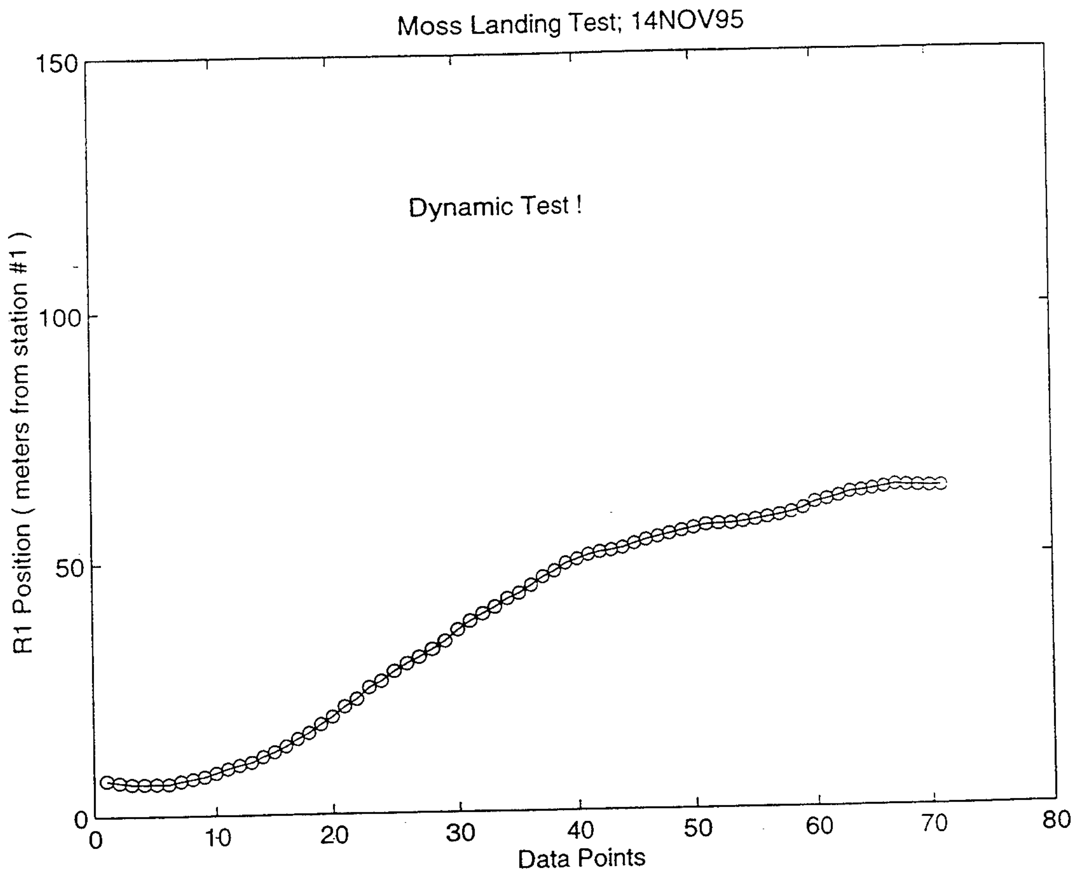


Figure 64. R1 Position Data for Test #121.

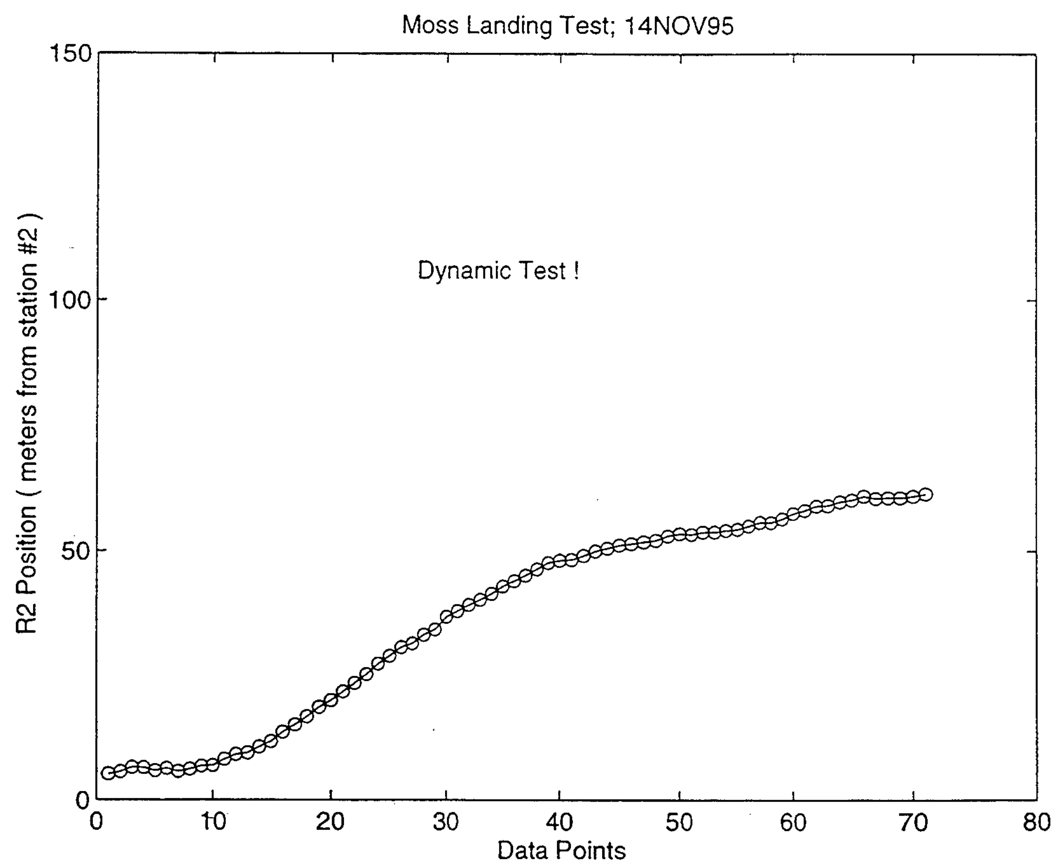


Figure 65. R2 Position Data for Test #121.

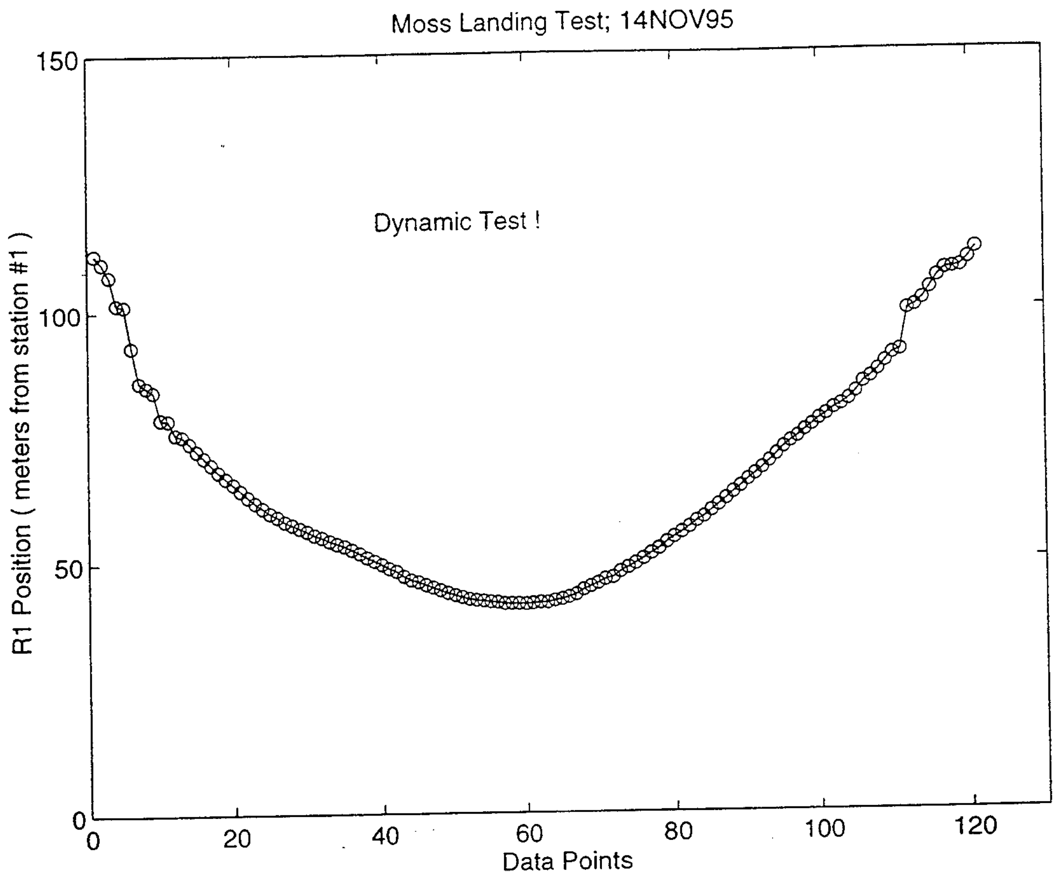


Figure 66. R1 Position Data for Test #124.

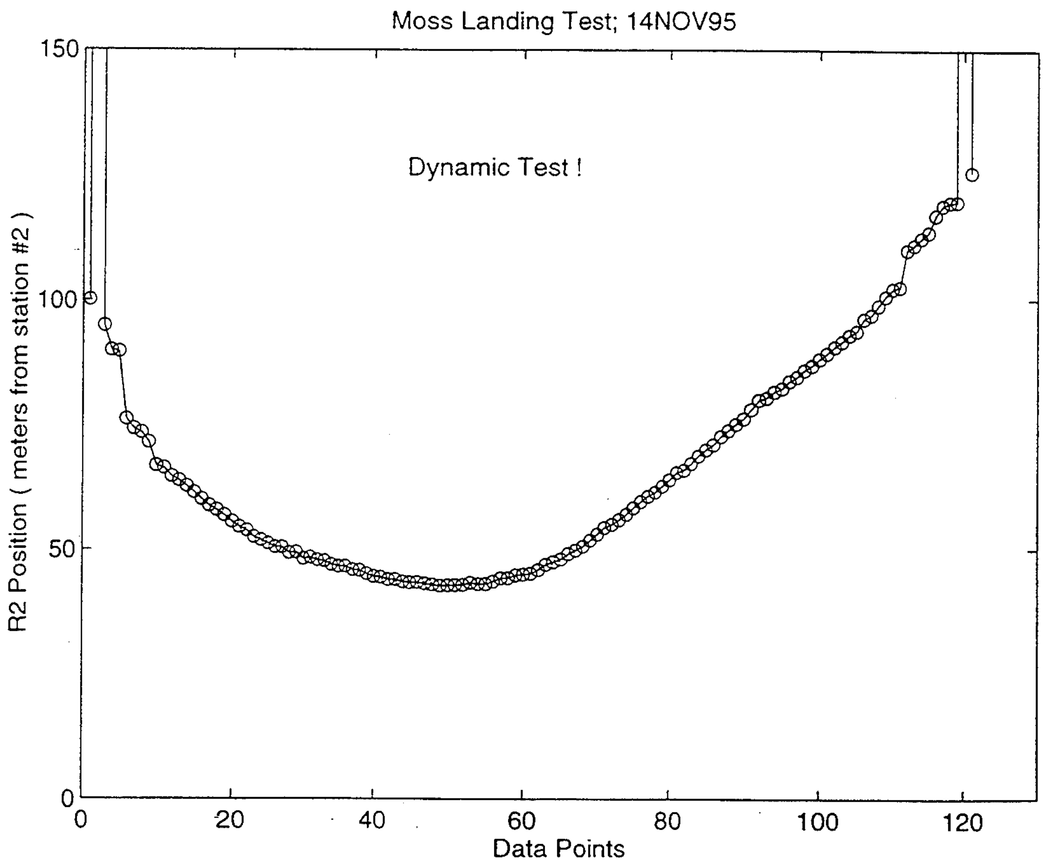


Figure 67. R2 Position Data for Test #124.

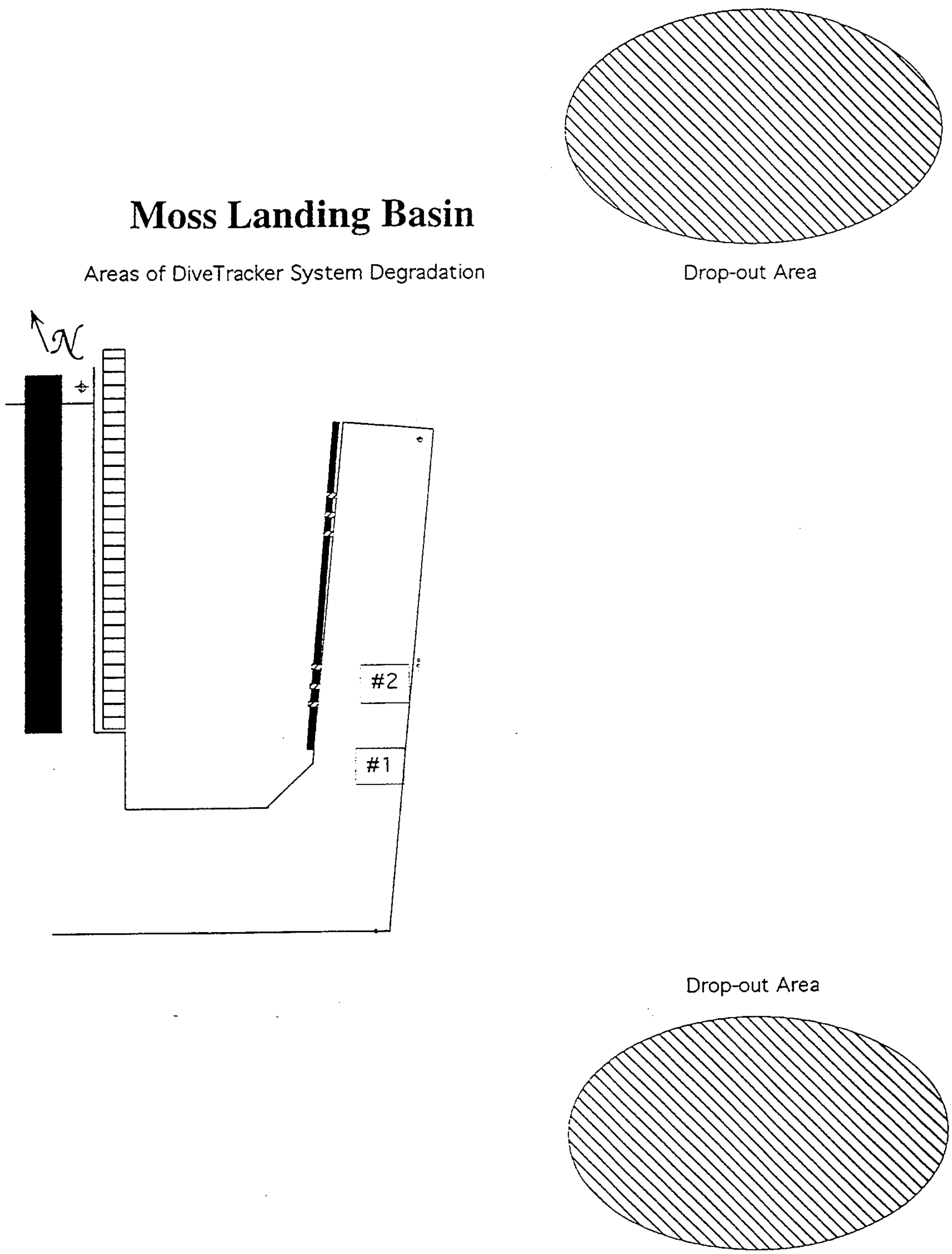


Figure 68. Areas of DiveTracker System Degradation.

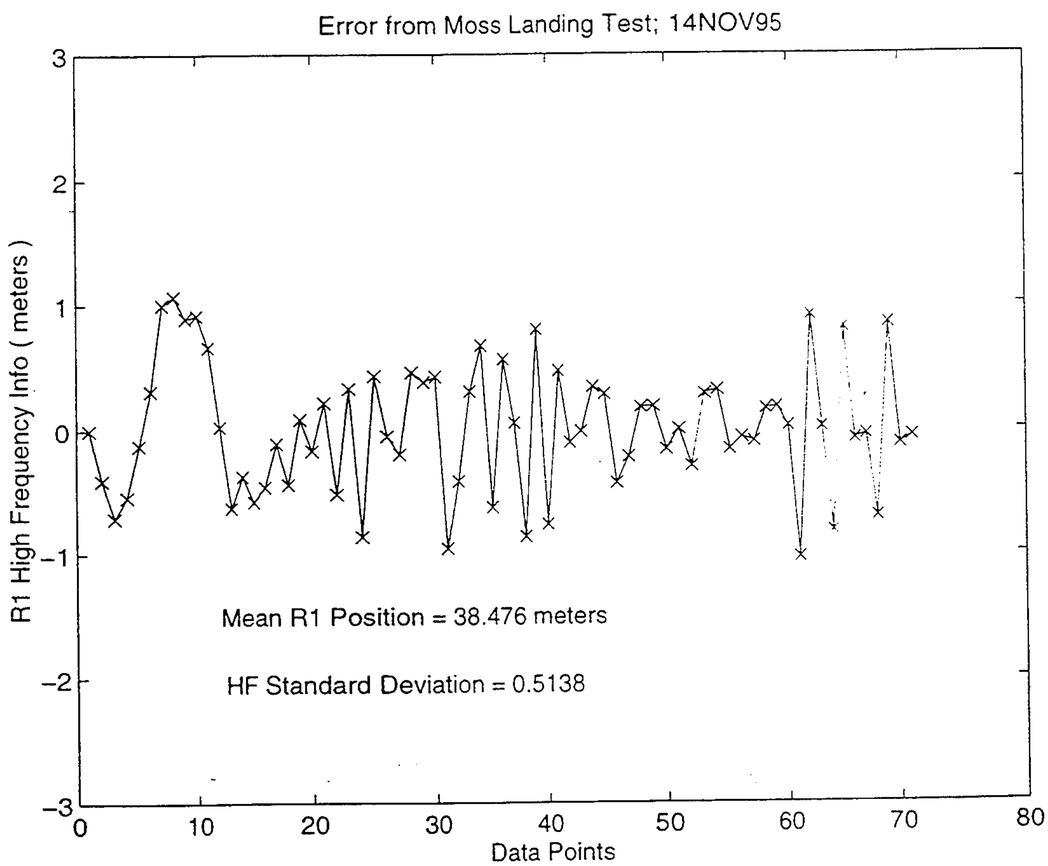


Figure 69. R1 High Frequency Data for Test #121.

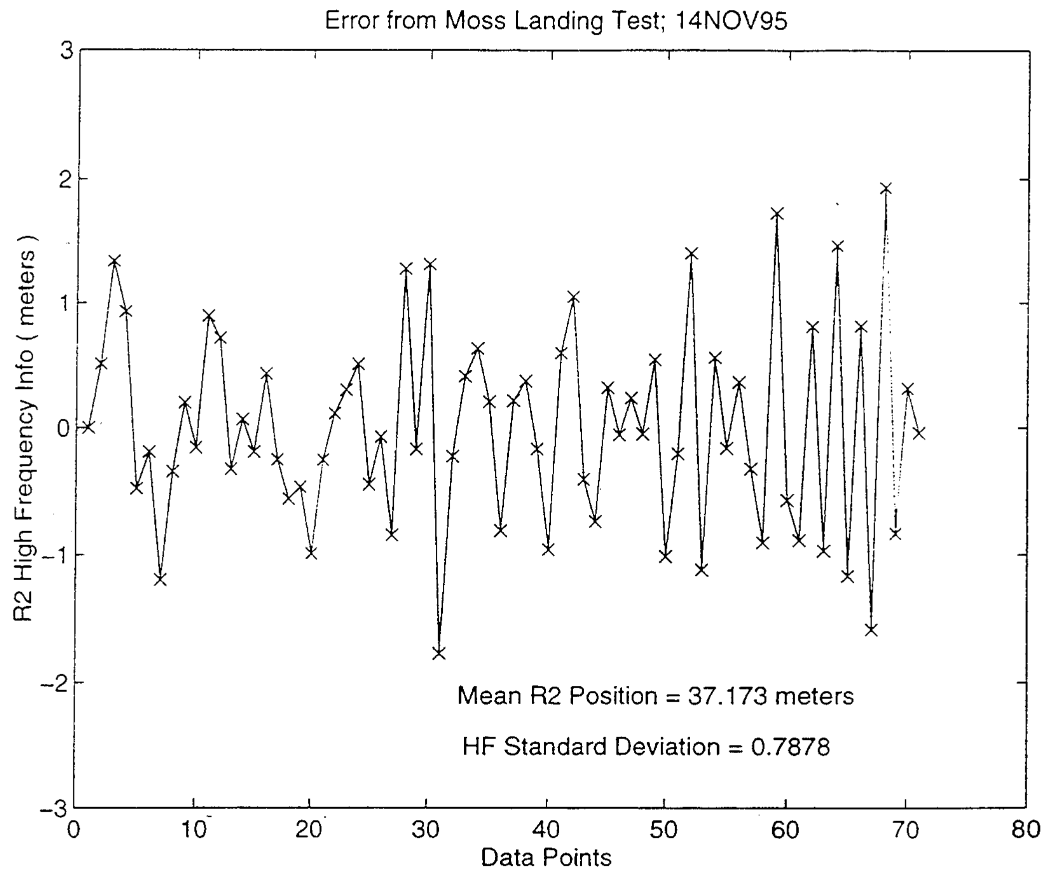


Figure 70. R2 High Frequency Data for Test #121.

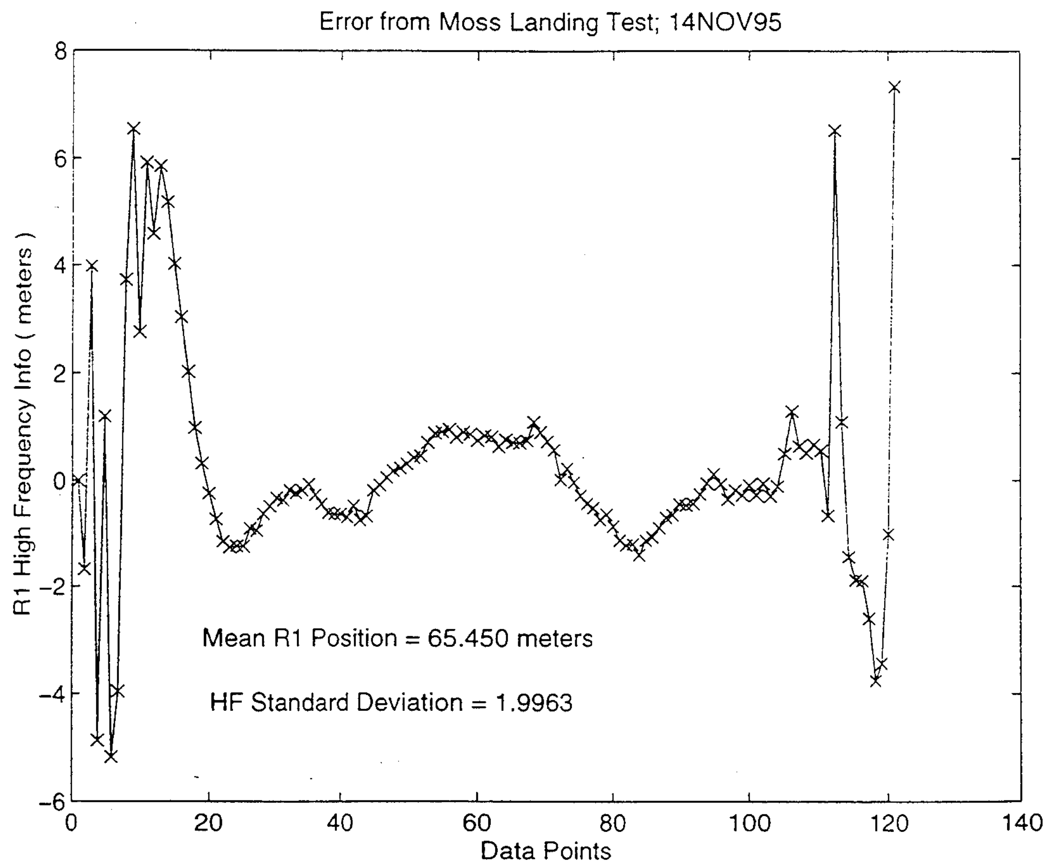


Figure 71. R1 High Frequency Data for Test #124.

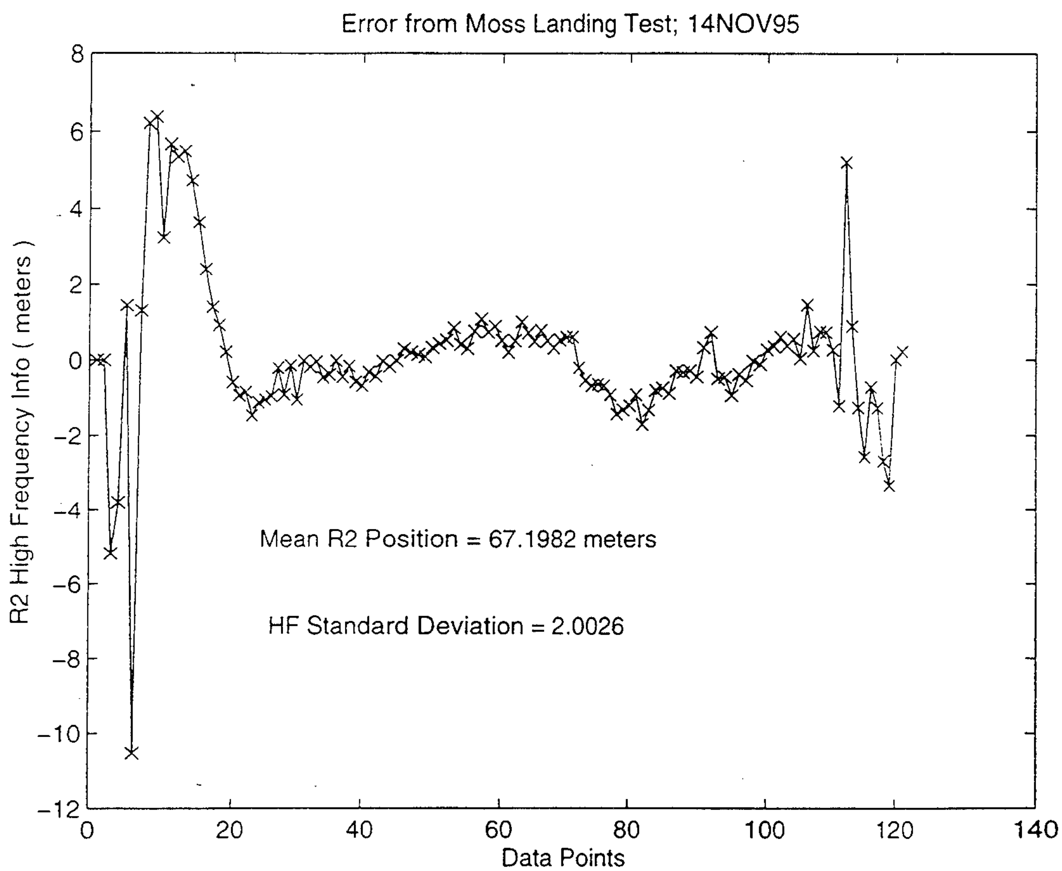


Figure 72. R2 High Frequency Data for Test #124.

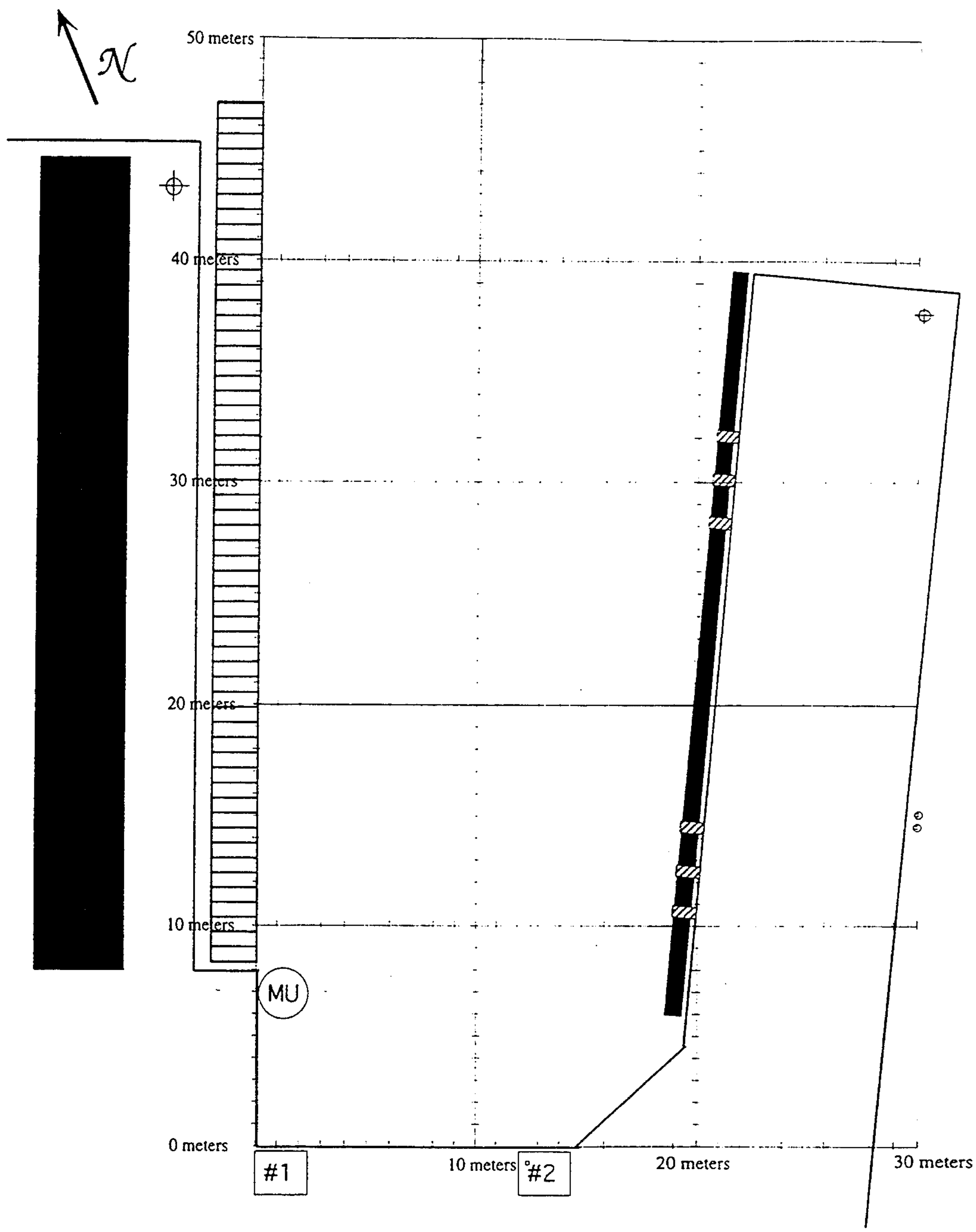


Figure 73. Equipment Set-up for Tests #130, #131, #132, and #133.

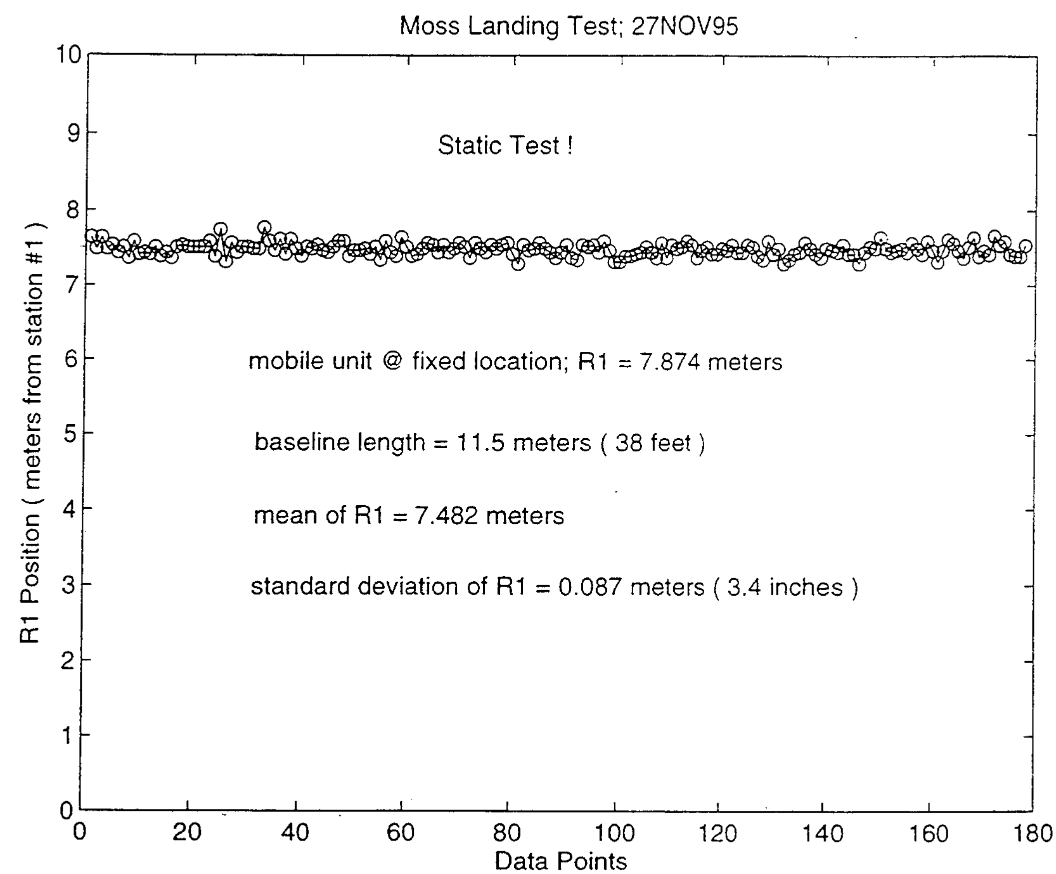


Figure 74. R1 Position Data for Test #130.

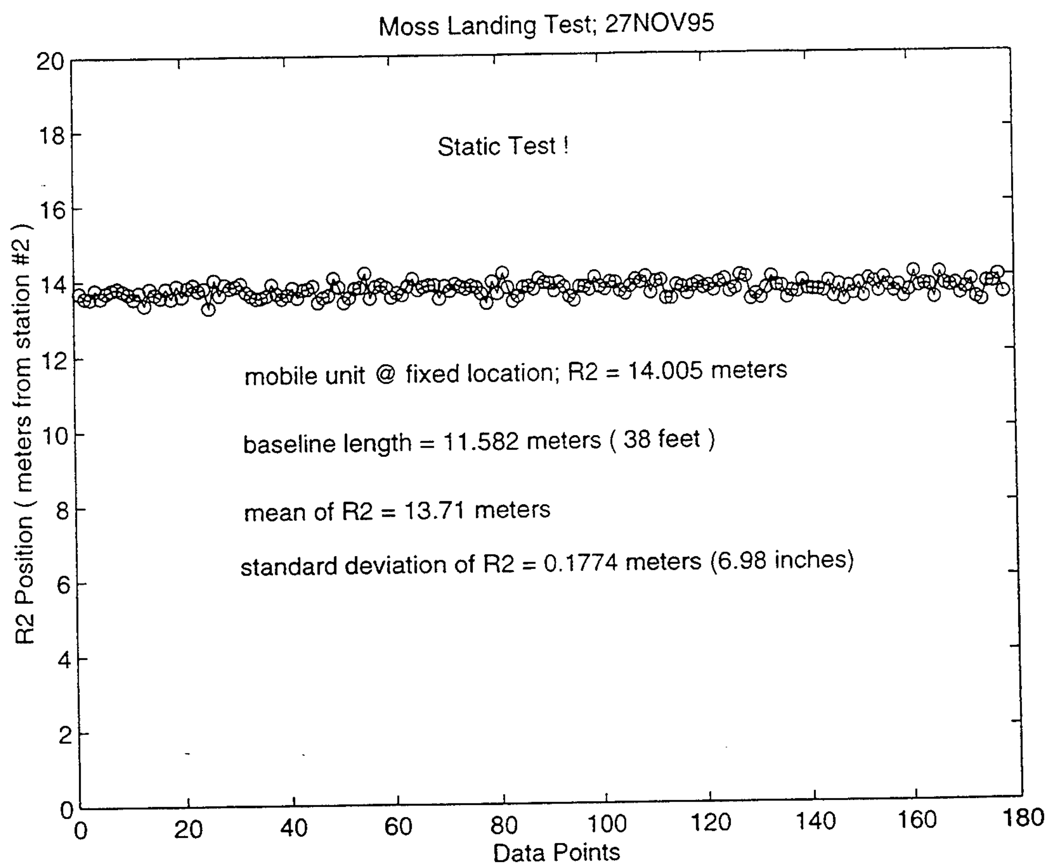


Figure 75. R2 Position Data for Test #130.

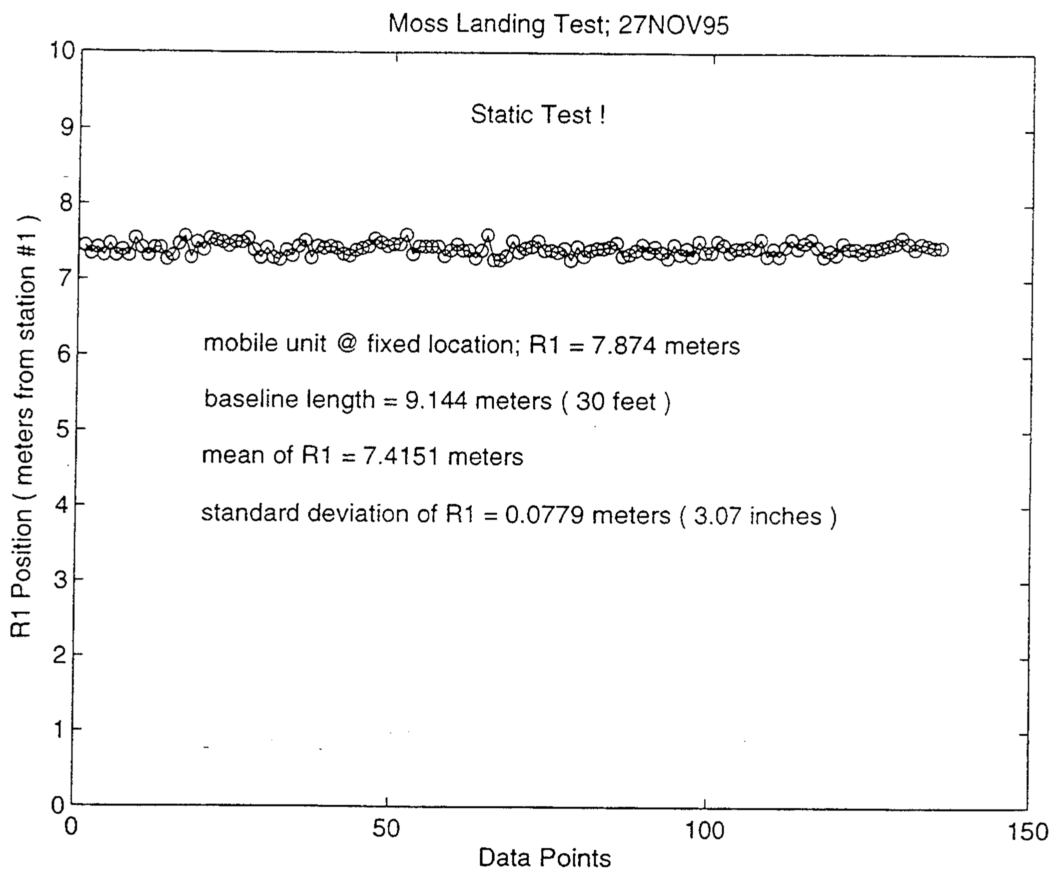


Figure 76. R1 Position Data for Test #131.

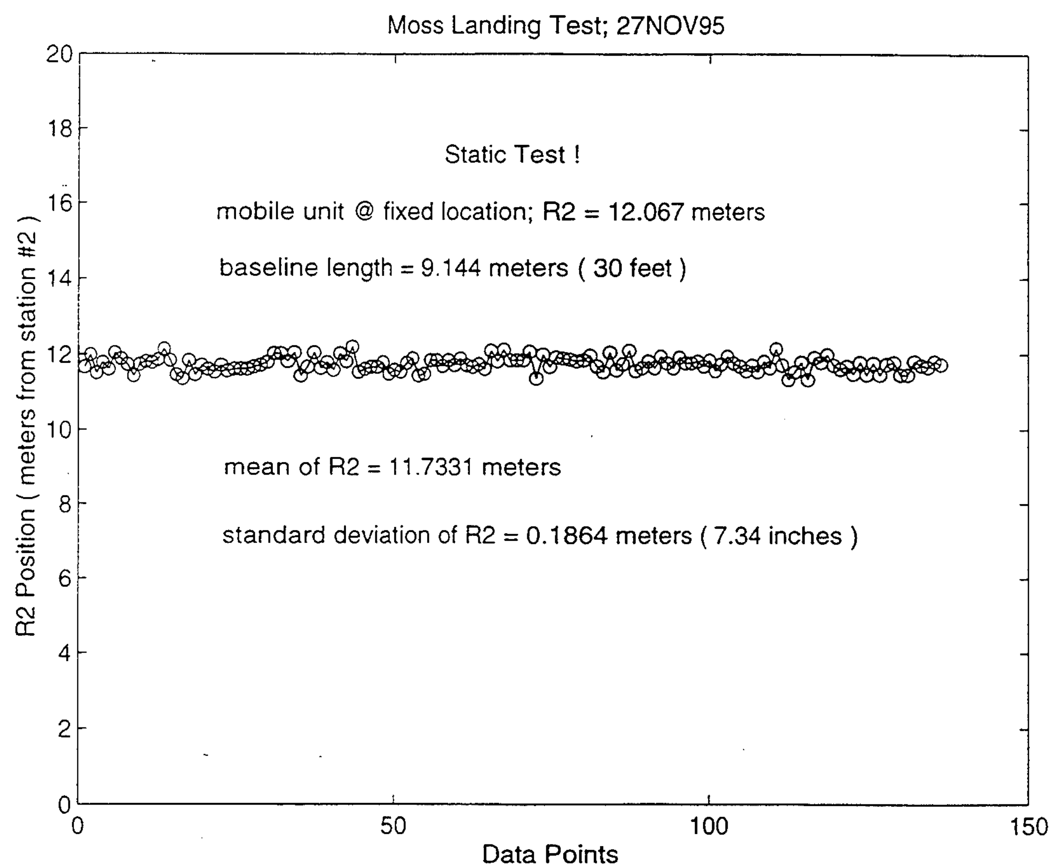


Figure 77. R2 Position Data for Test #131.

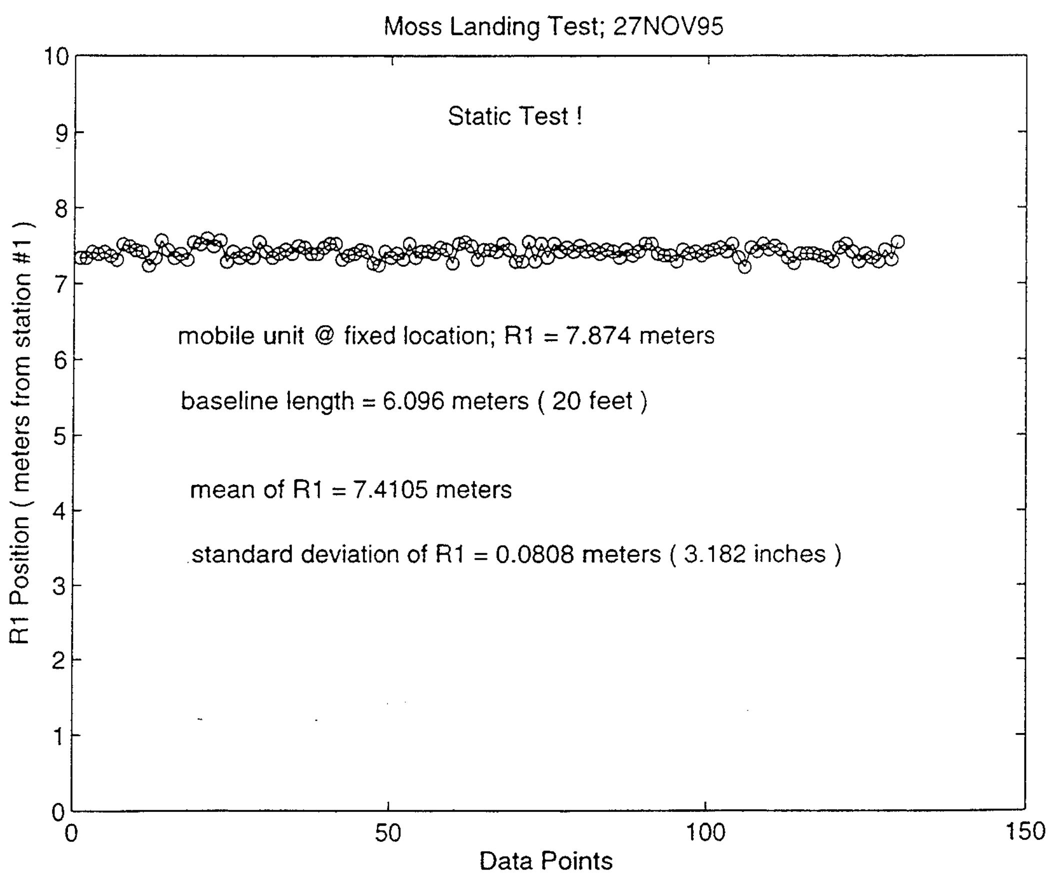


Figure 78. R1 Position Data for Test #132.

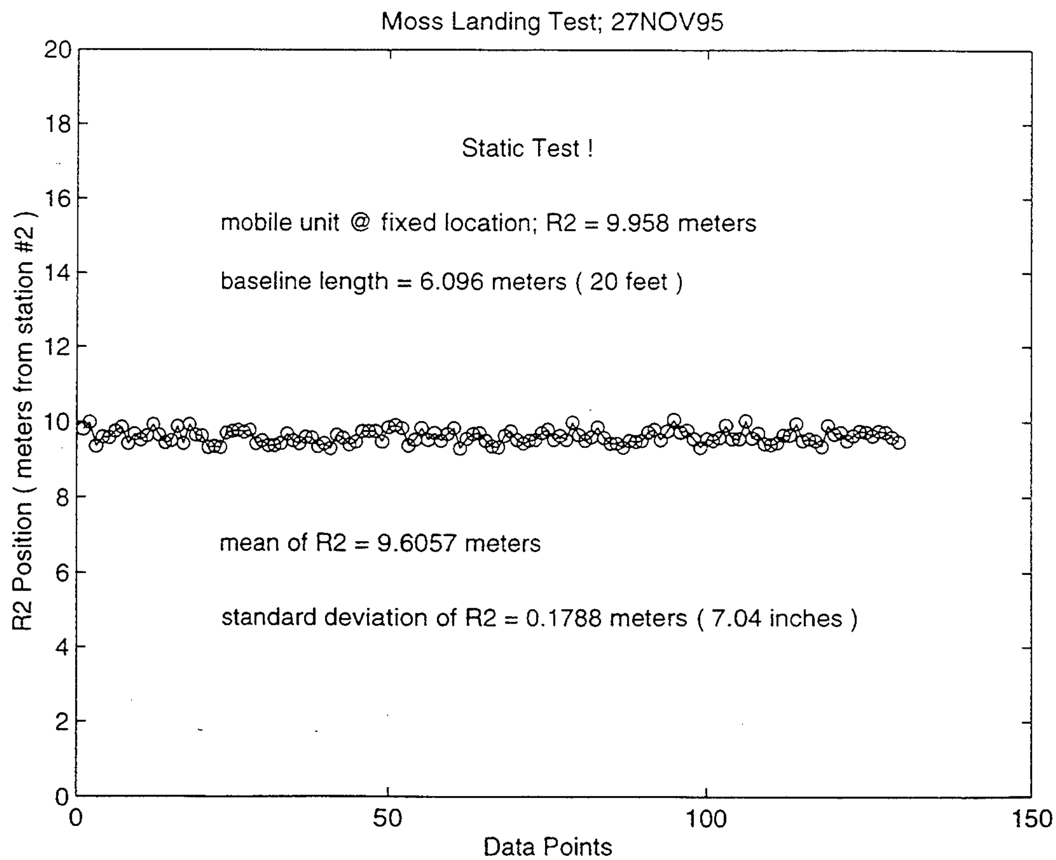


Figure 79. R2 Position Data for Test #132.

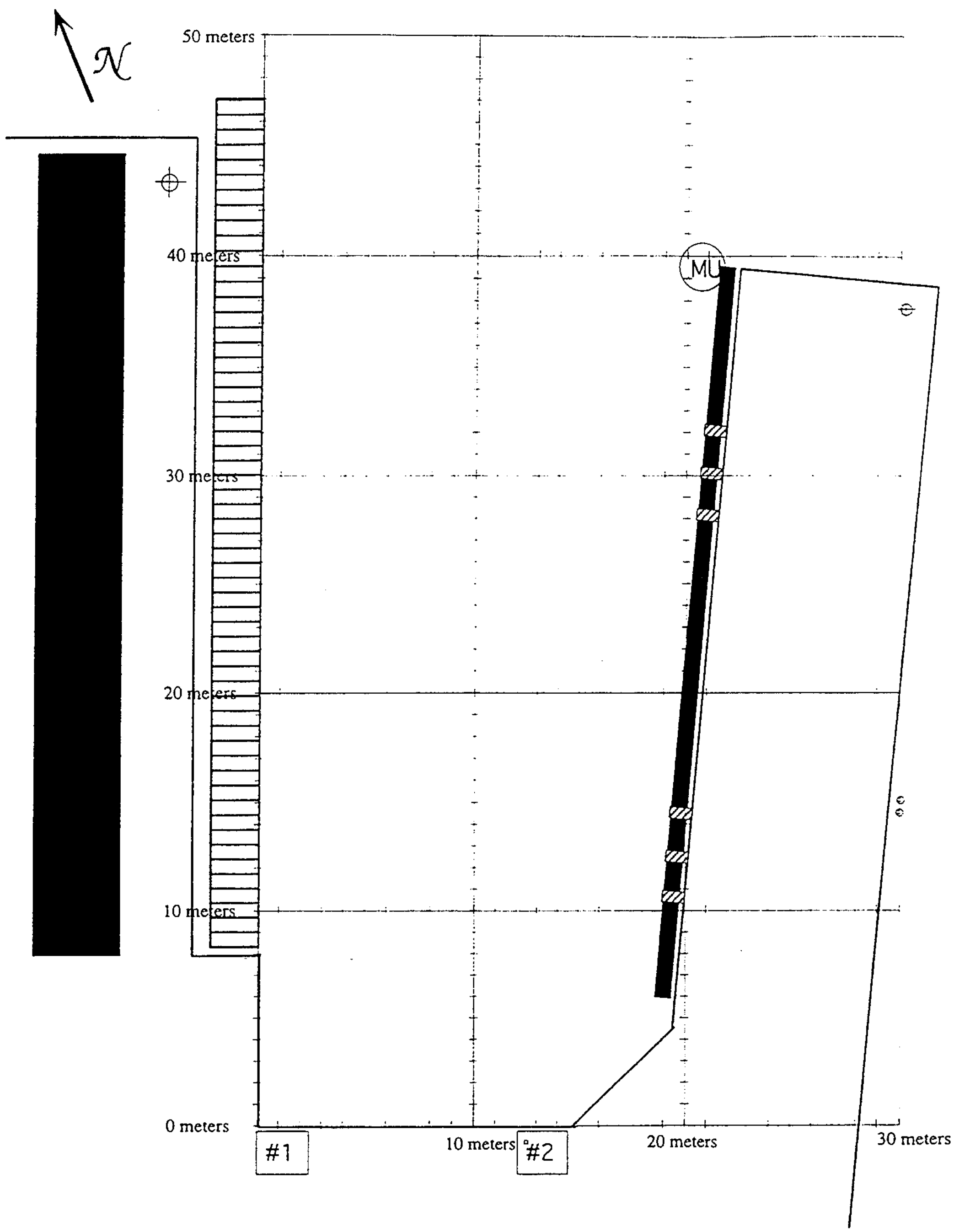


Figure 80. Equipment Set-up for Tests #136, #137, #138, and #139.

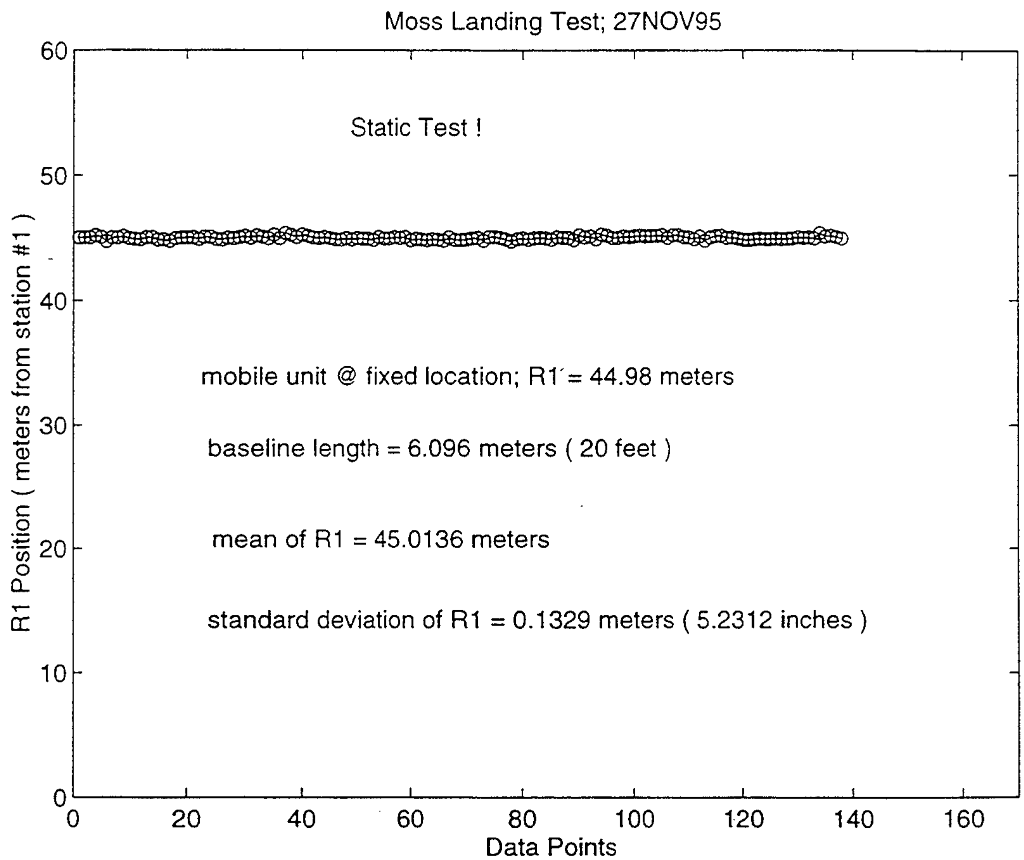


Figure 81. R1 Position Data for Test #136.

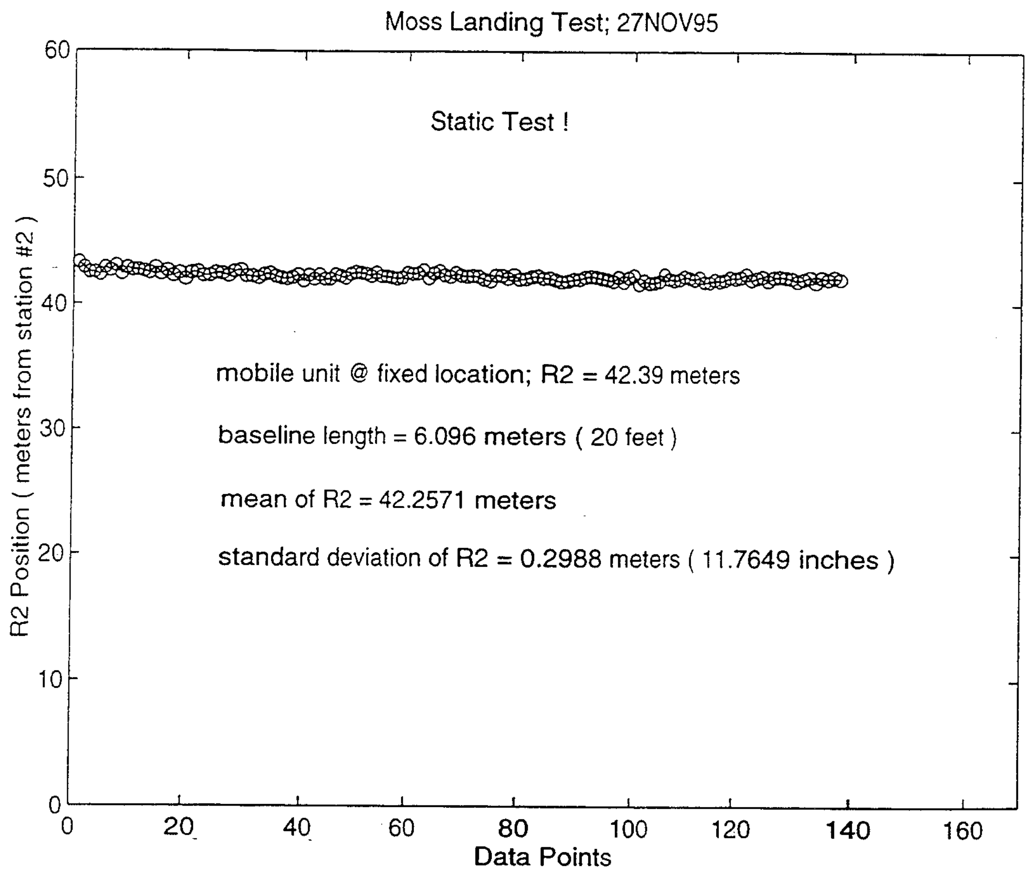


Figure 82. R2 Position Data for Test #136.

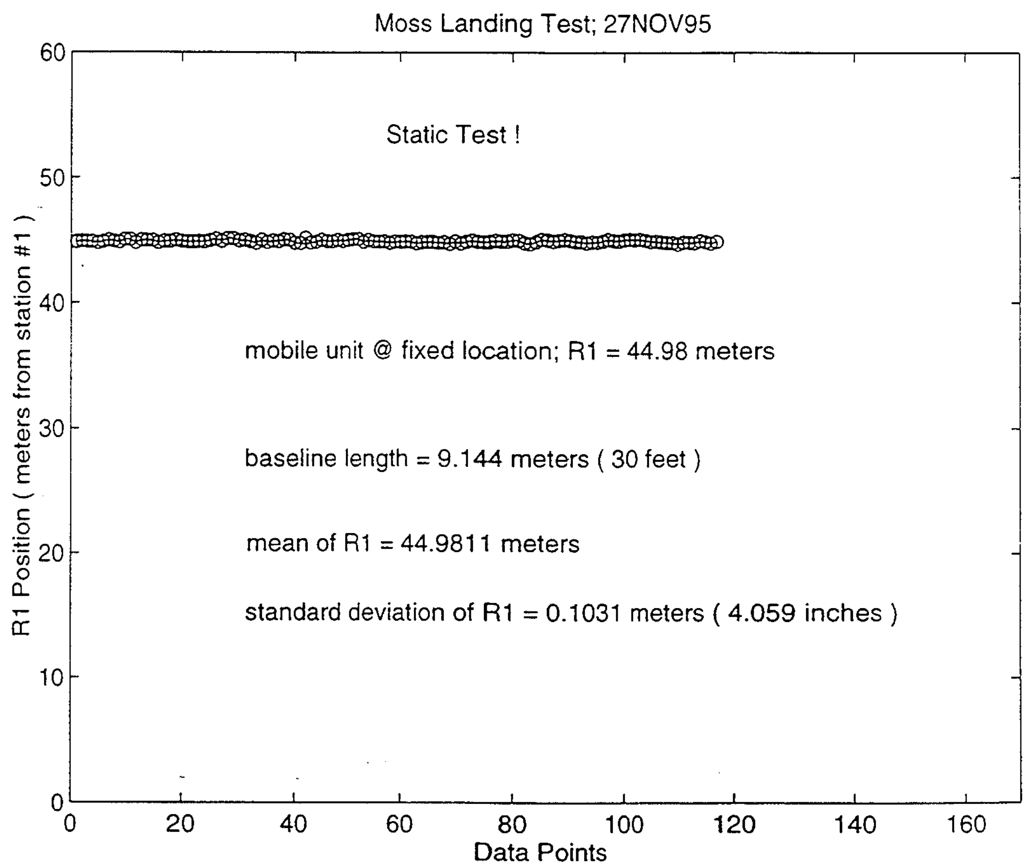


Figure 83. R1 Position Data for Test #137.

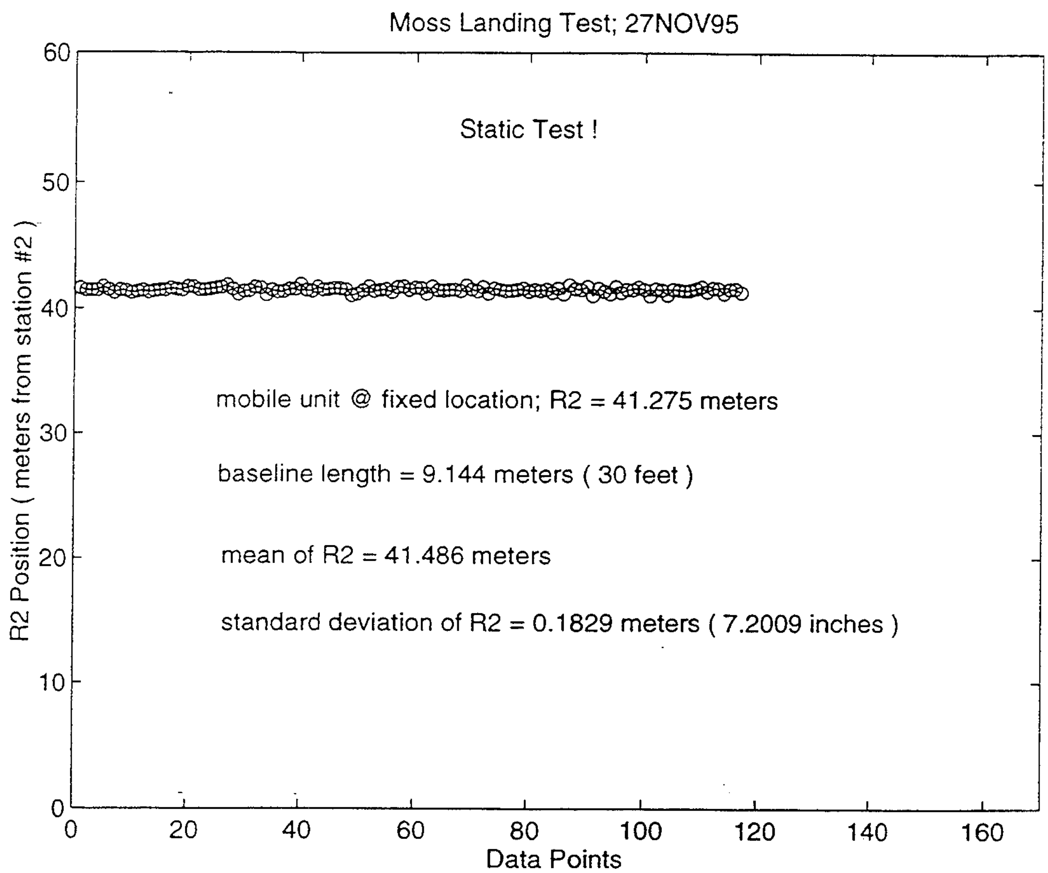


Figure 84. R2 Position Data for Test #137.

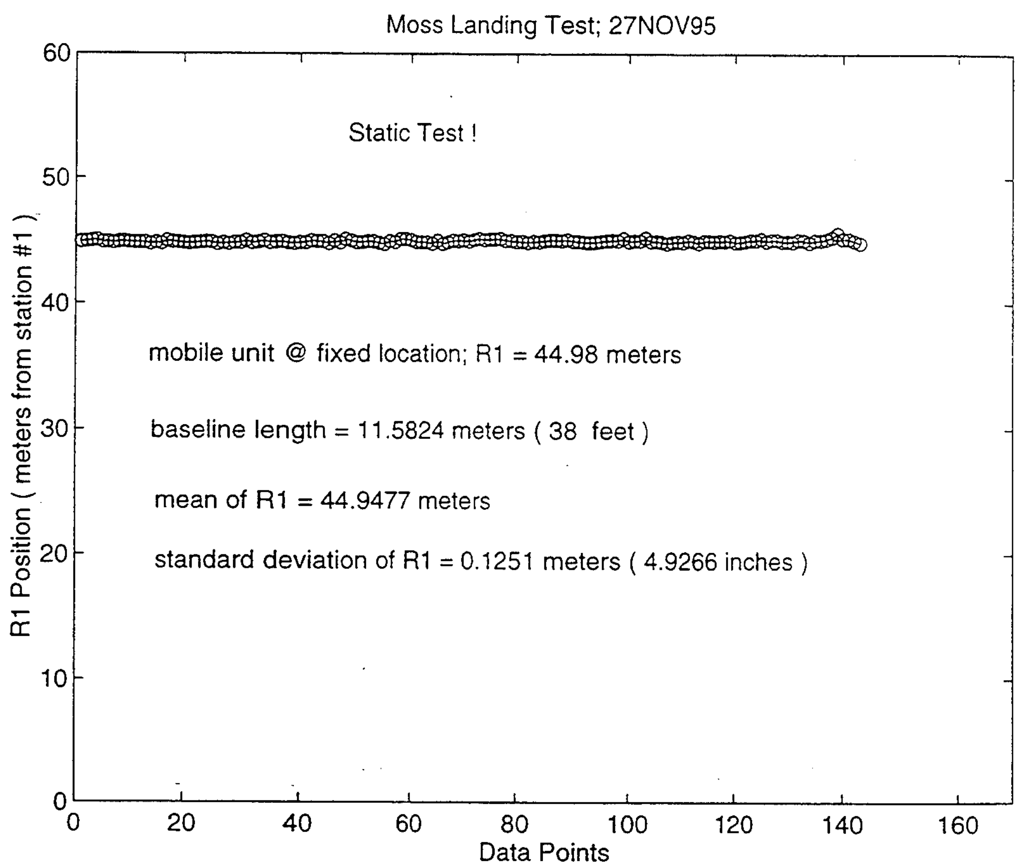


Figure 85. R1 Position Data for Test #138.

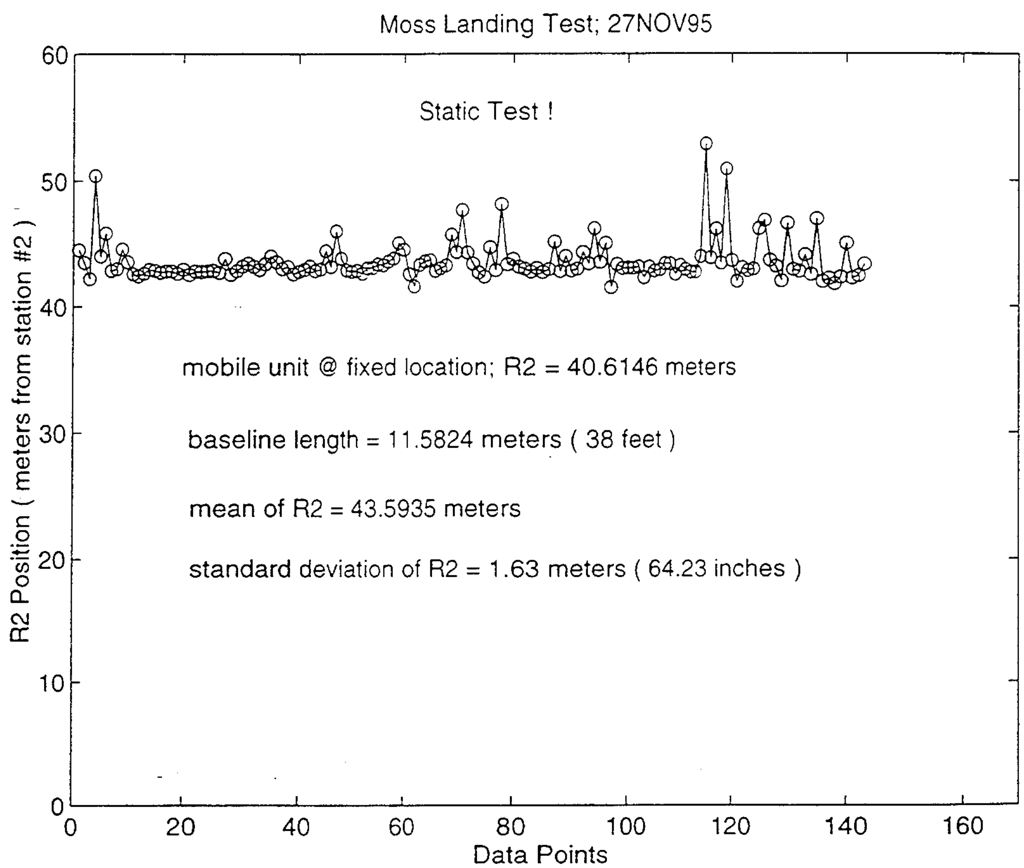


Figure 86. R2 Position Data for Test #138.

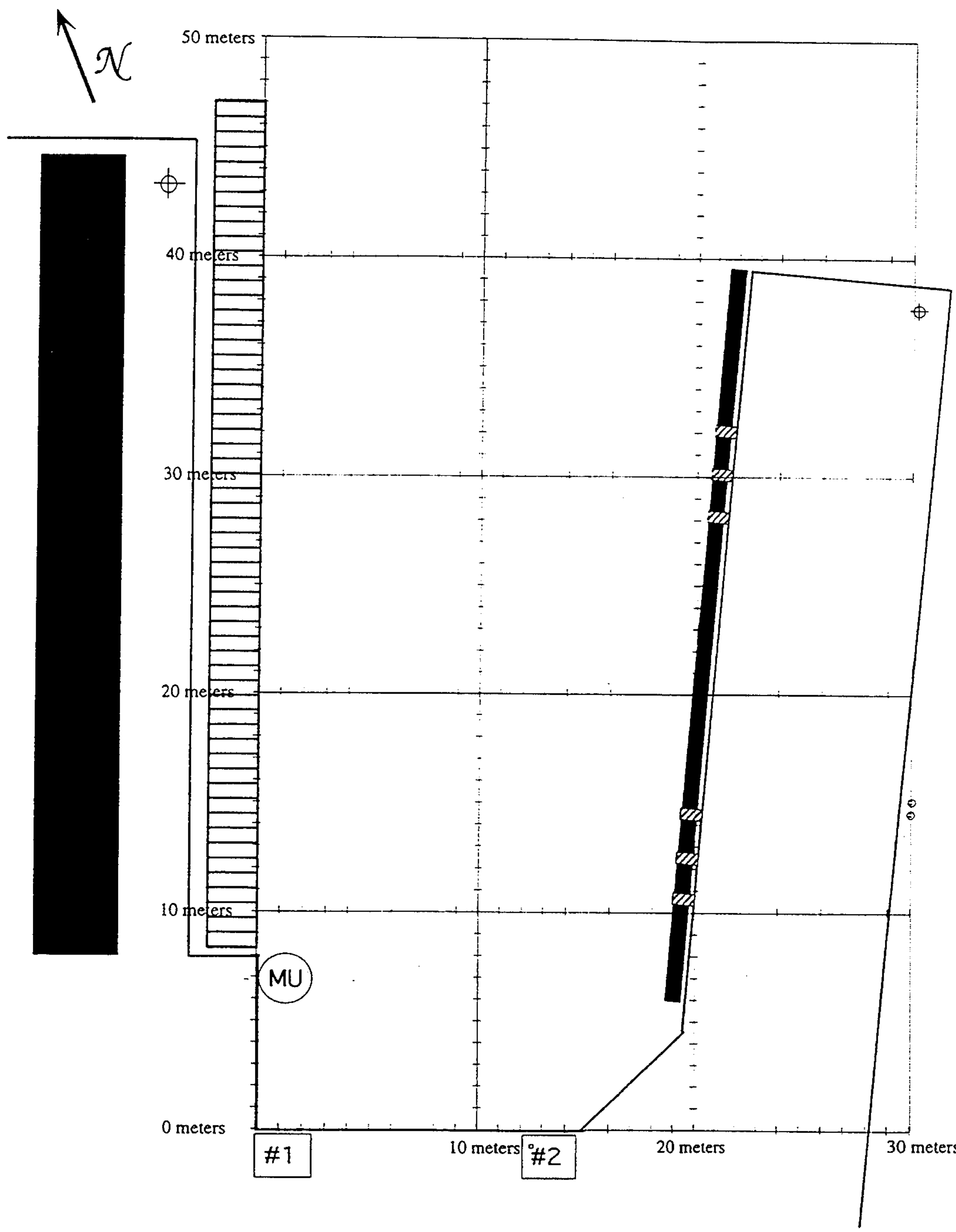


Figure 87. Equipment Set-up for Tests #155 through #160.

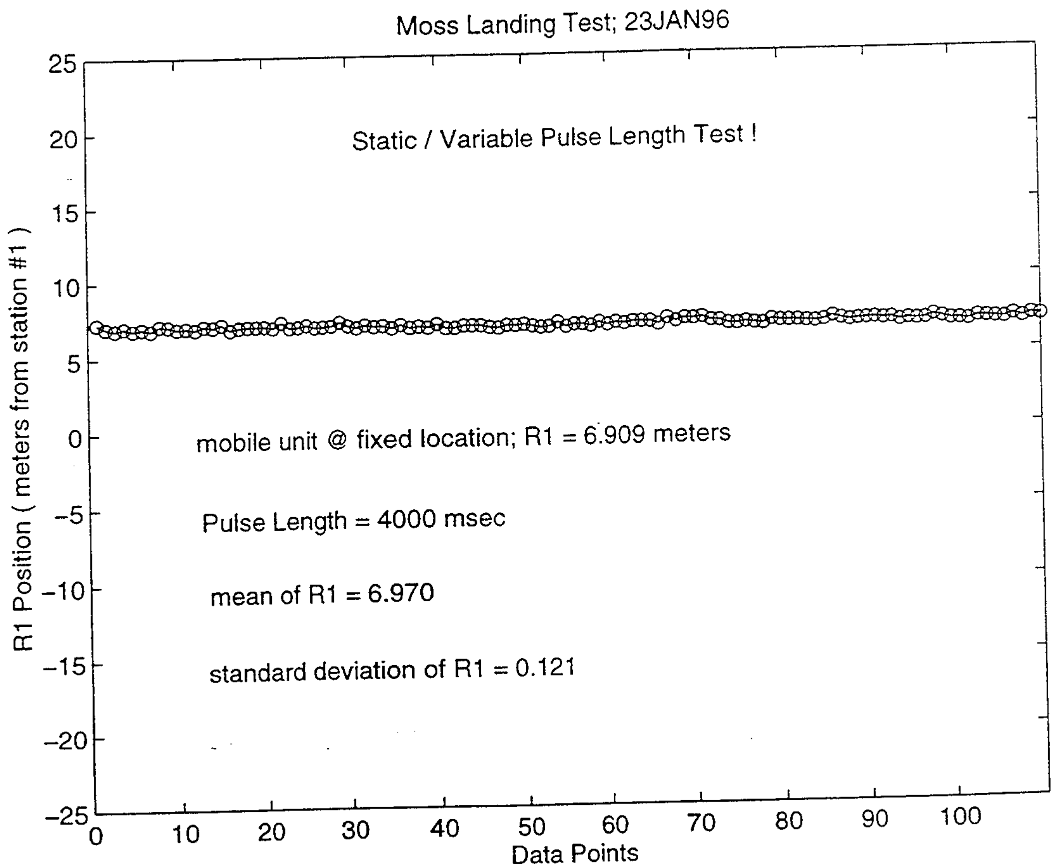


Figure 88. R1 Position Data for Test #155.

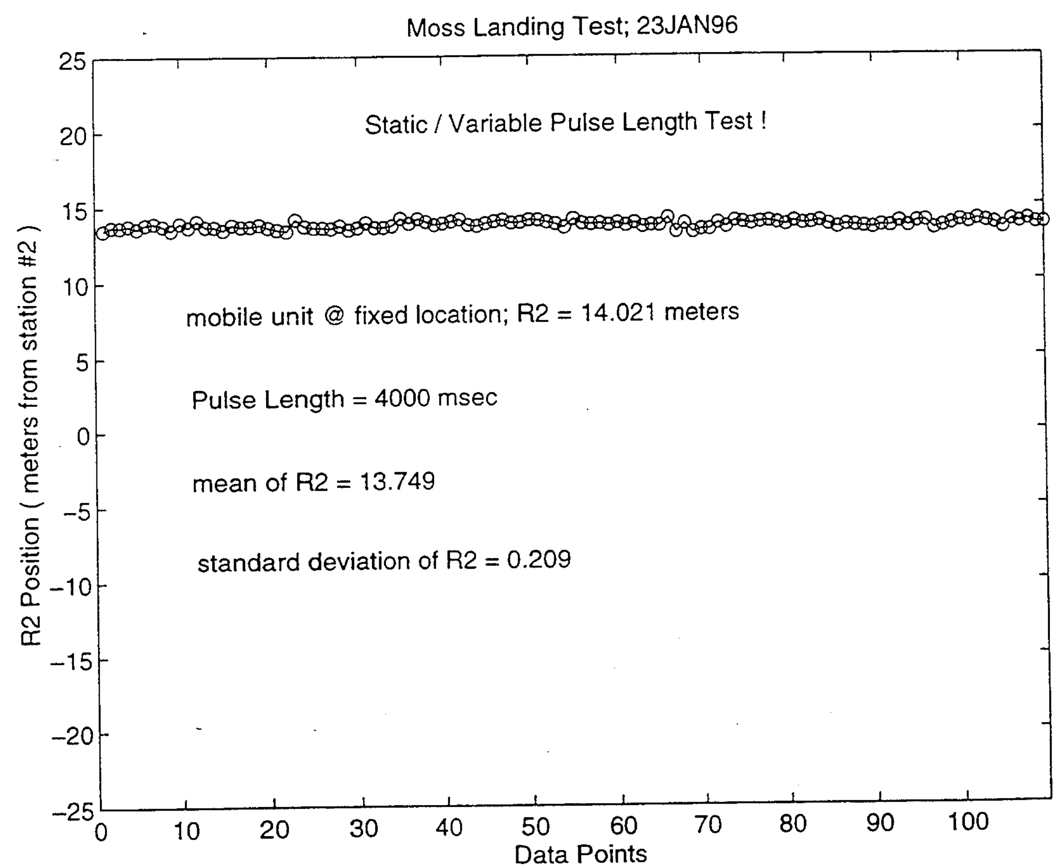


Figure 89. R2 Position Data for Test #155.

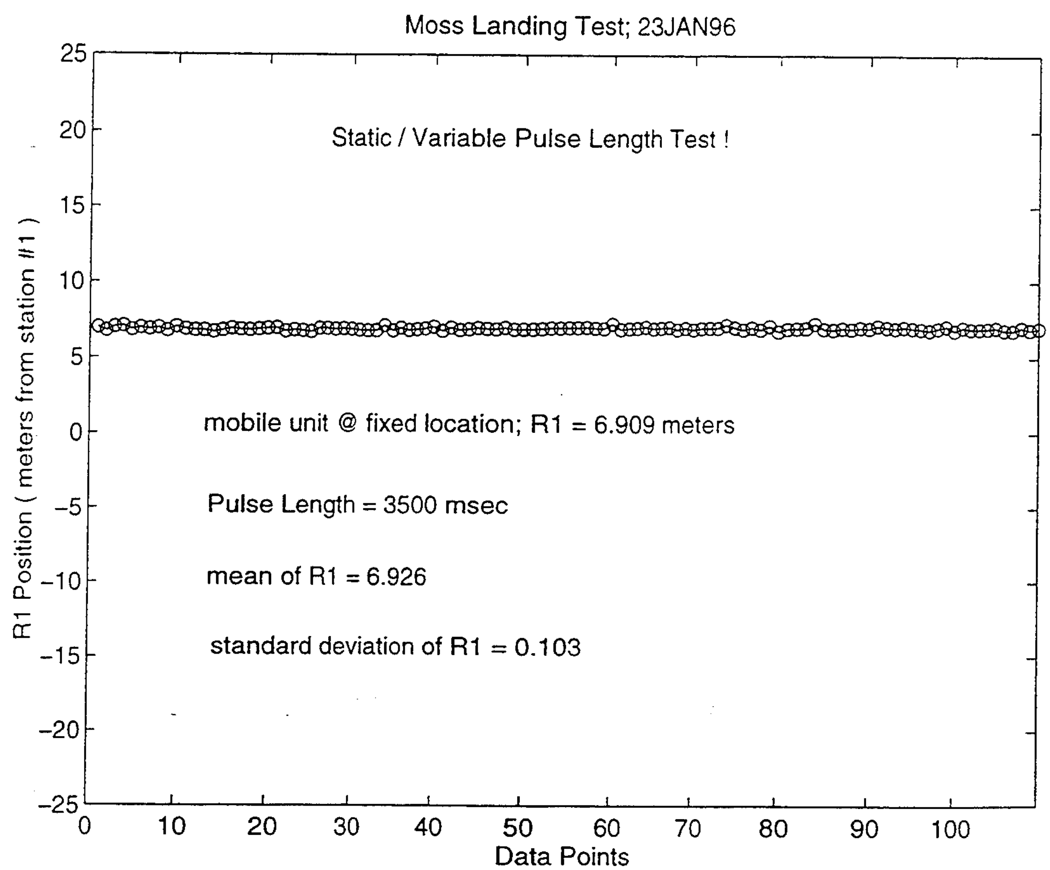


Figure 90. R1 Position Data for Test #155.

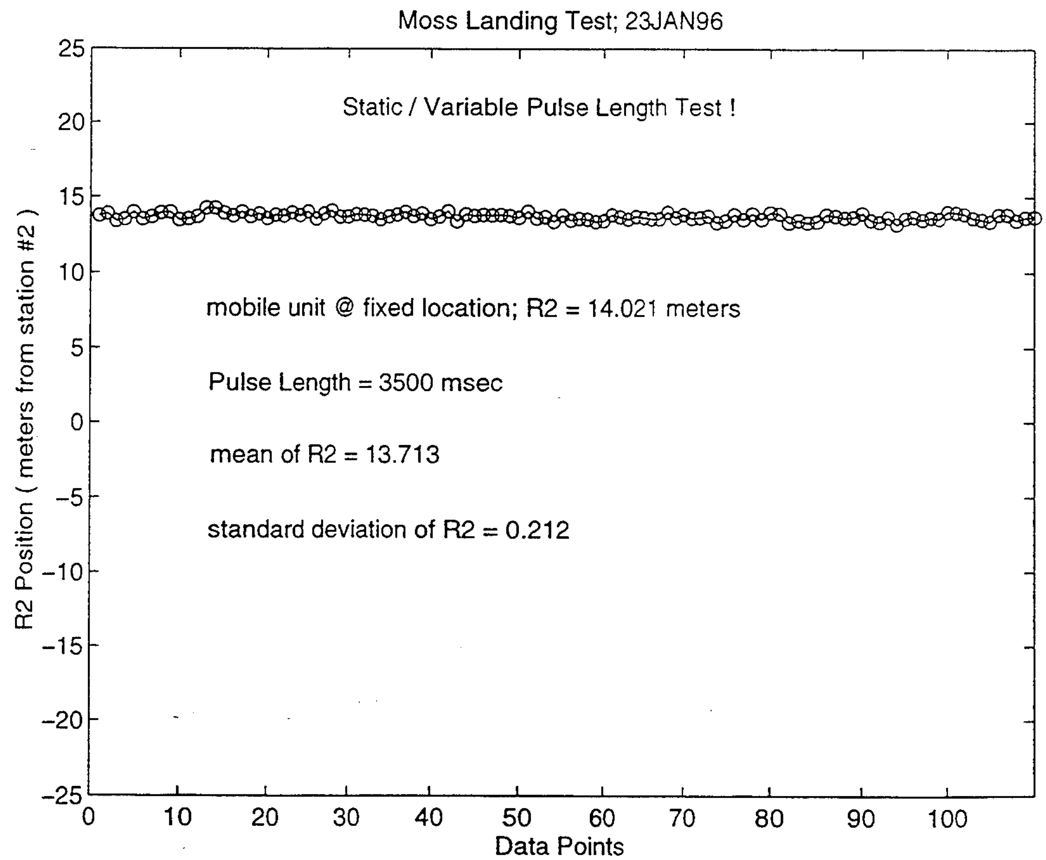


Figure 91. R2 Position Data for Test #156.

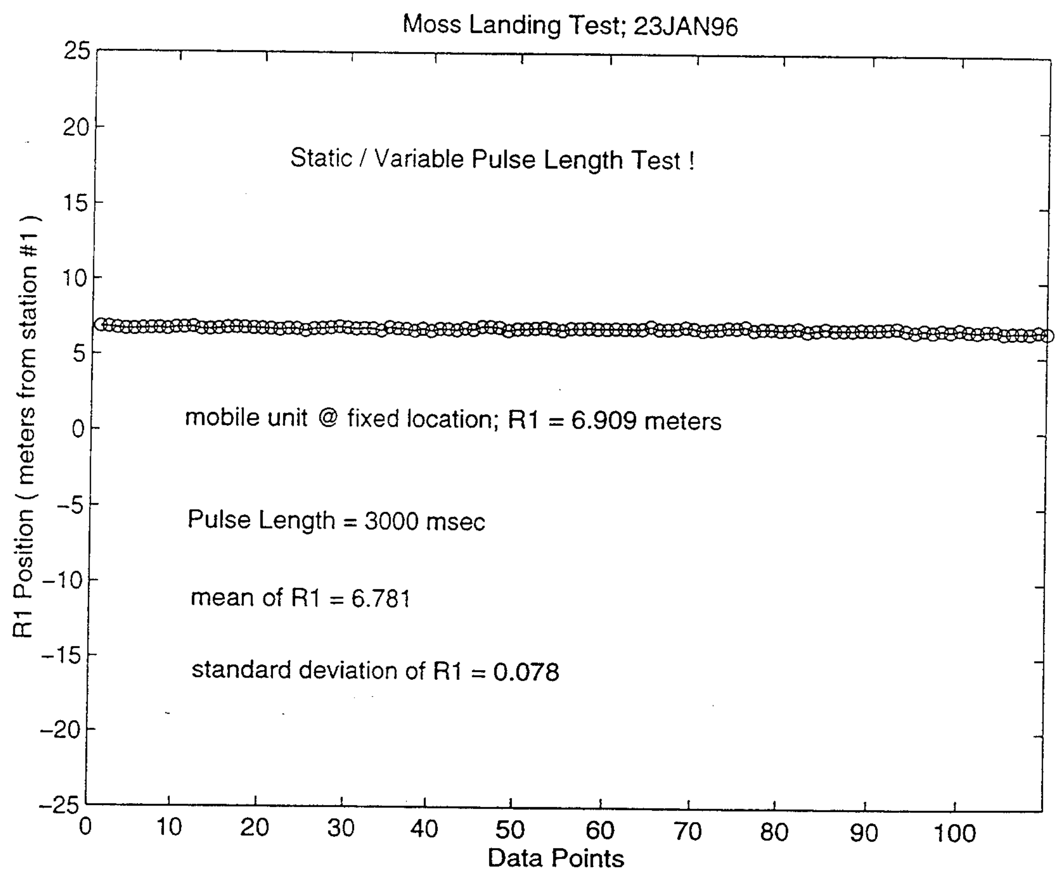


Figure 92. R1 Position Data for Test #157.

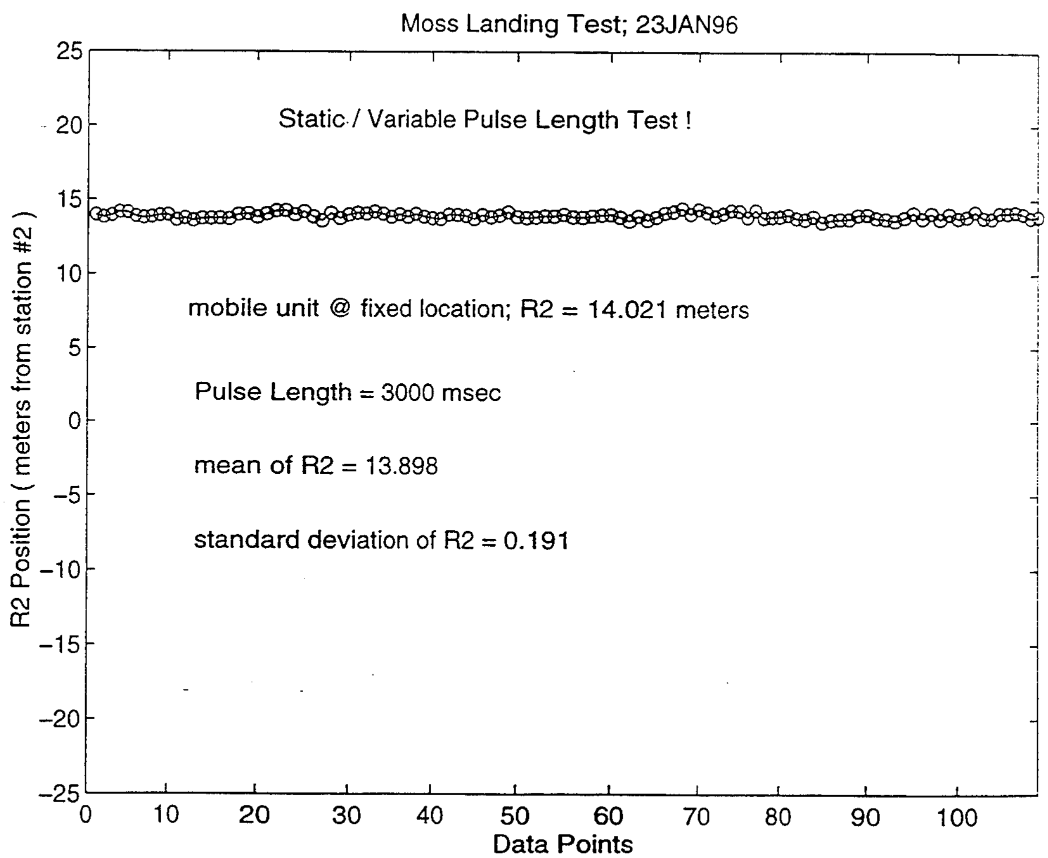


Figure 93. R2 Position Data for Test #157.

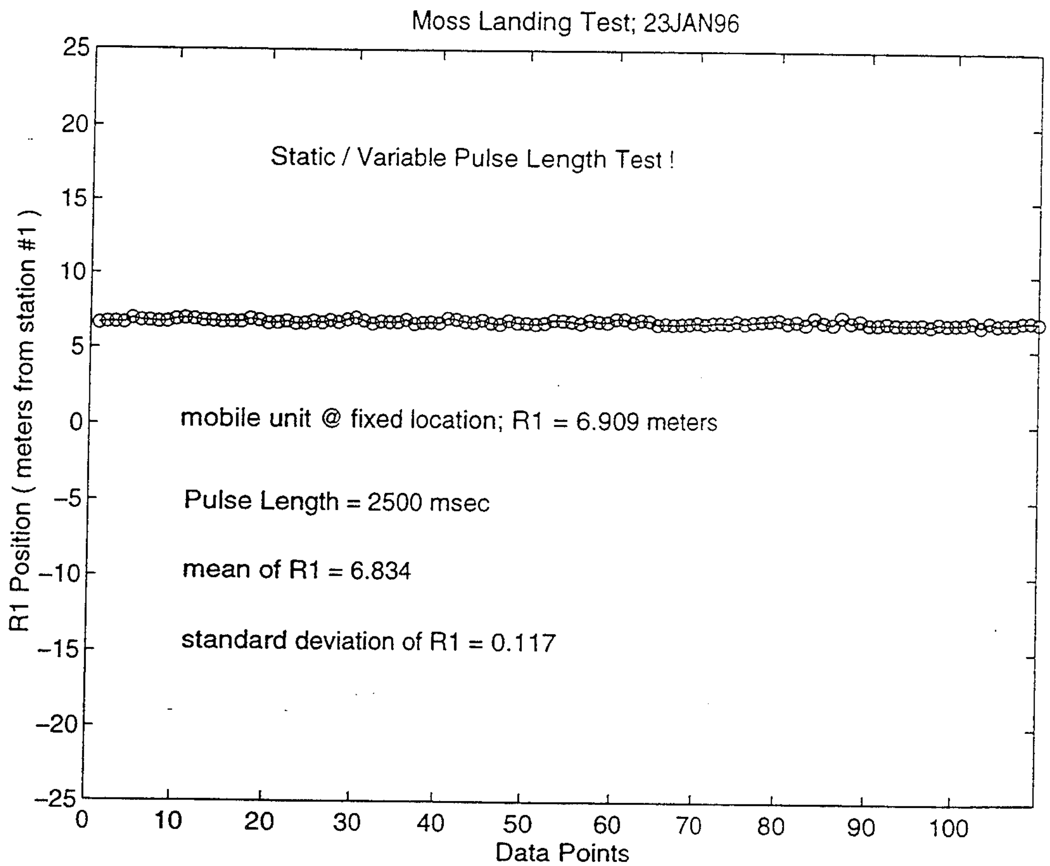


Figure 94. R1 Position Data for Test #158.

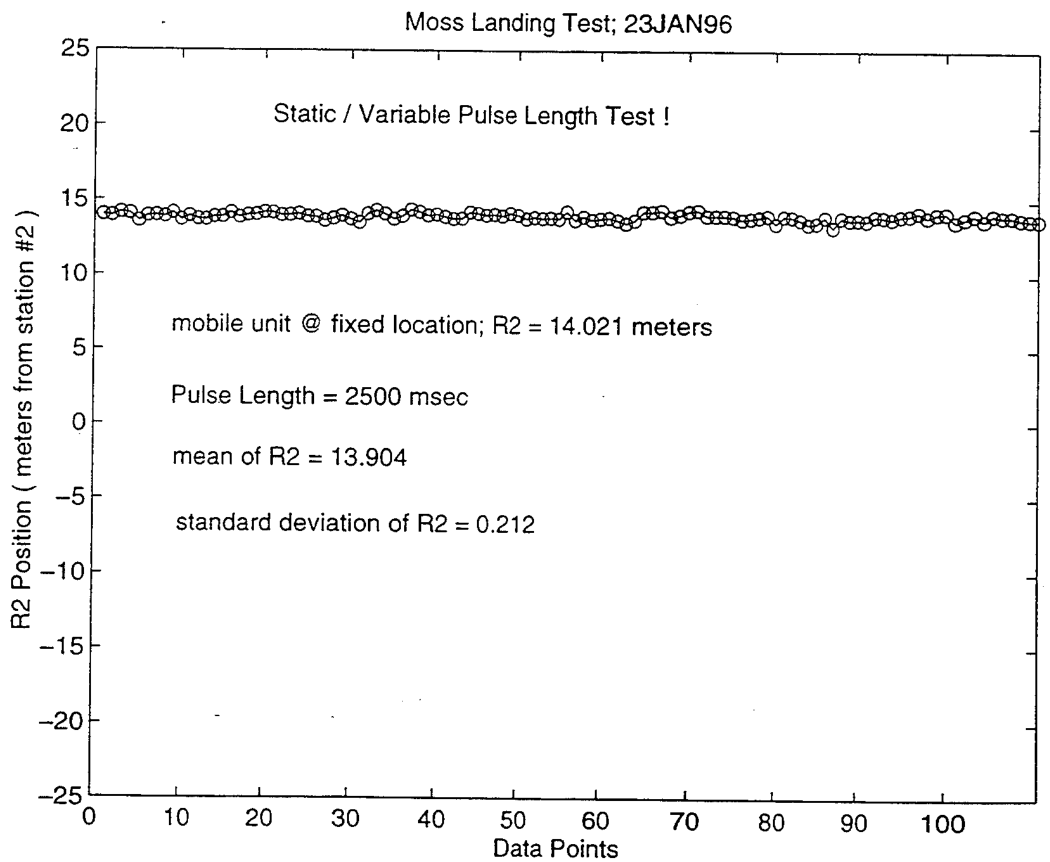


Figure 95. R2 Position Data for Test #158.

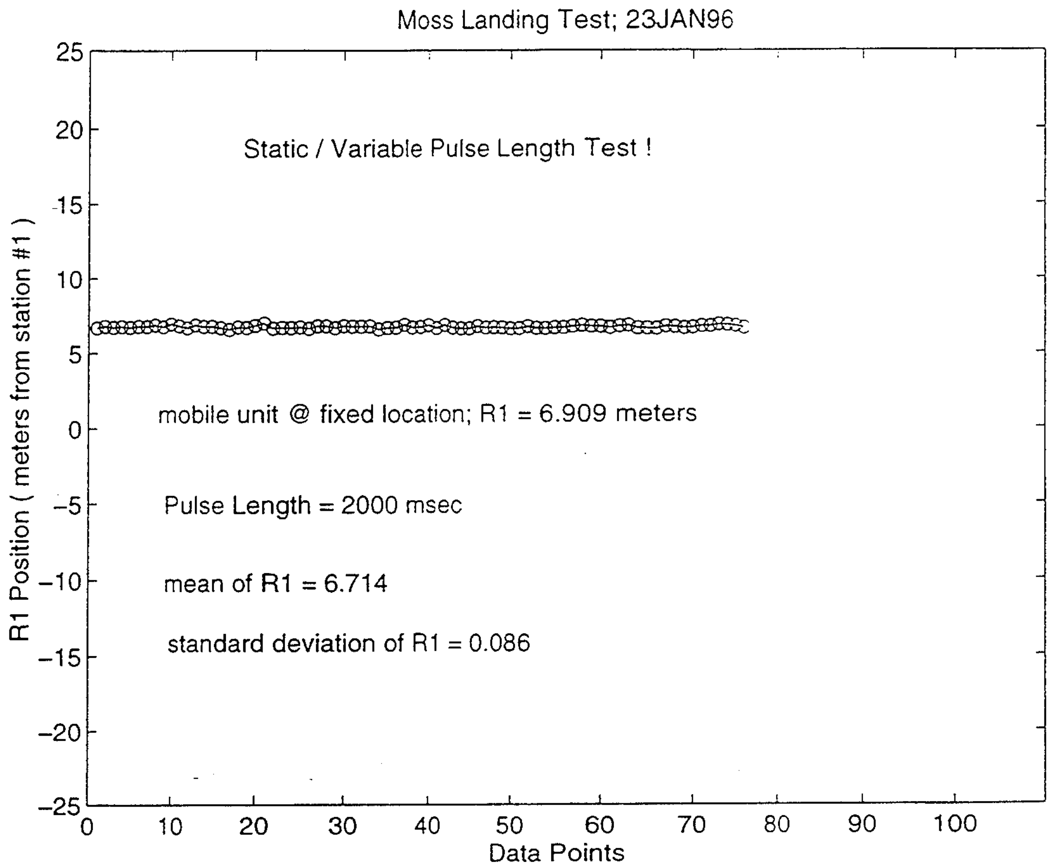


Figure 96. R1 Position Data for Test #159.

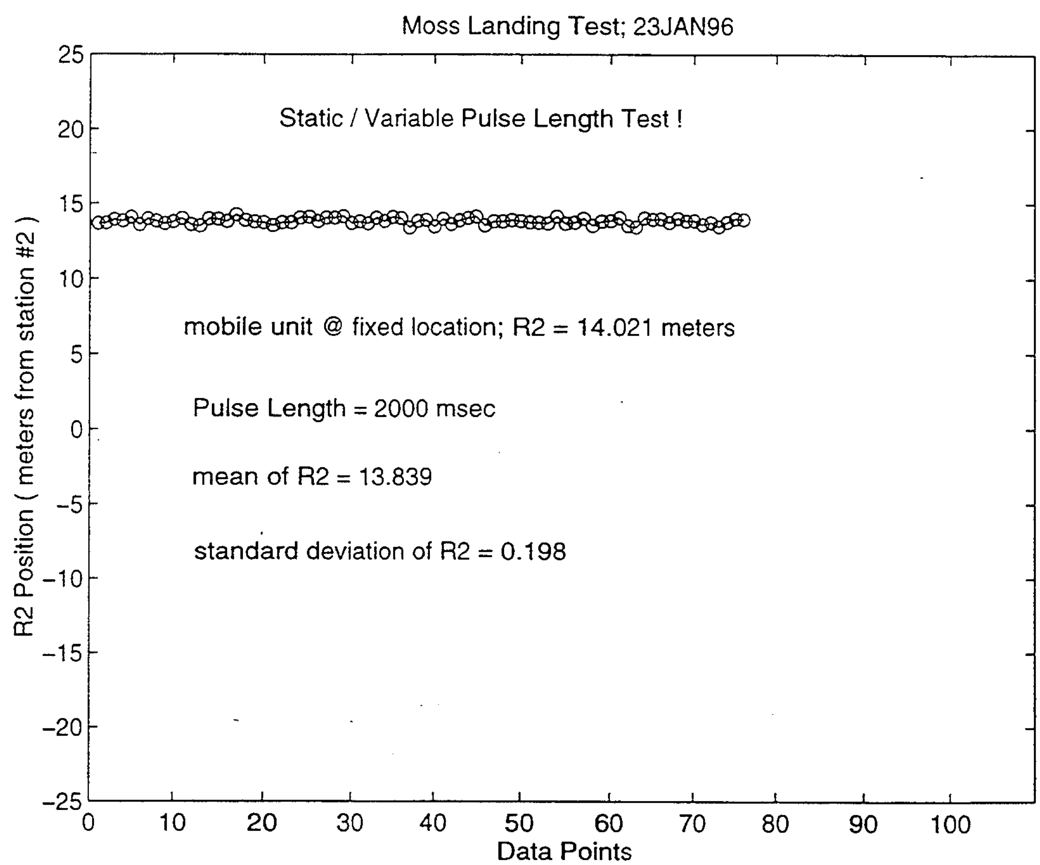


Figure 97. R2 Position Data for Test #159.

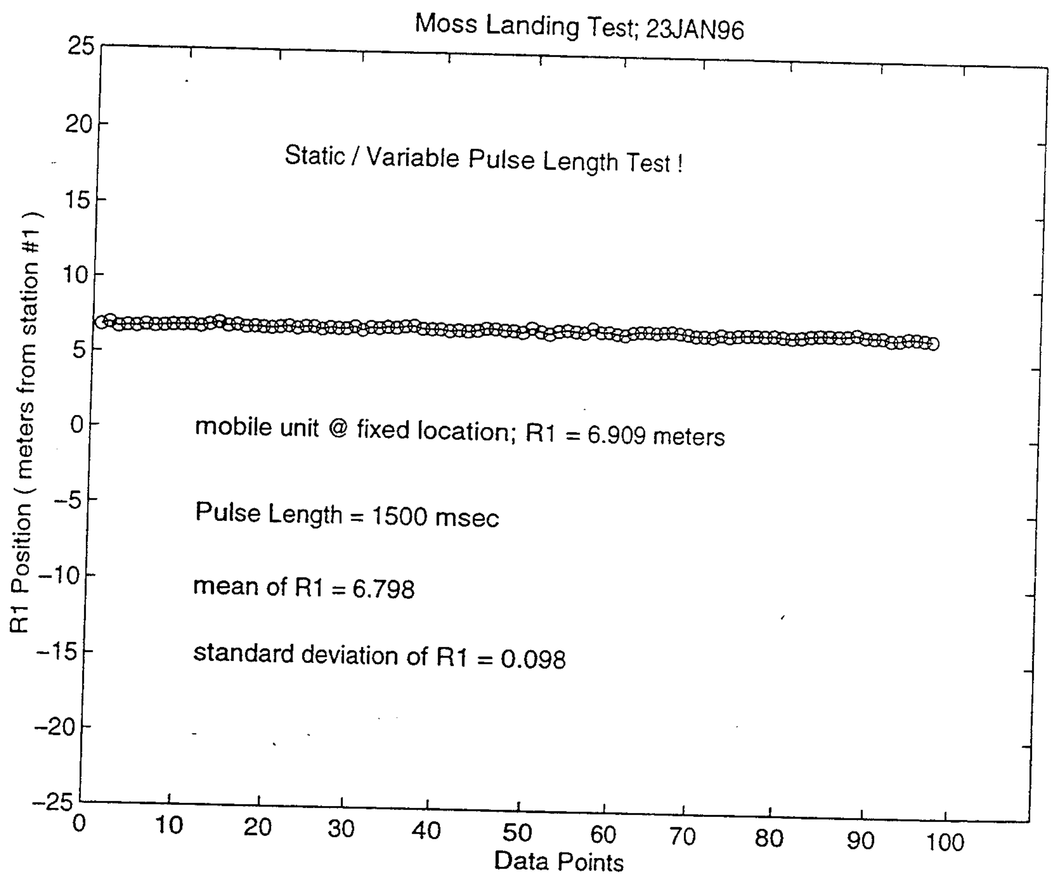


Figure 98. R1 Position Data for Test #160.

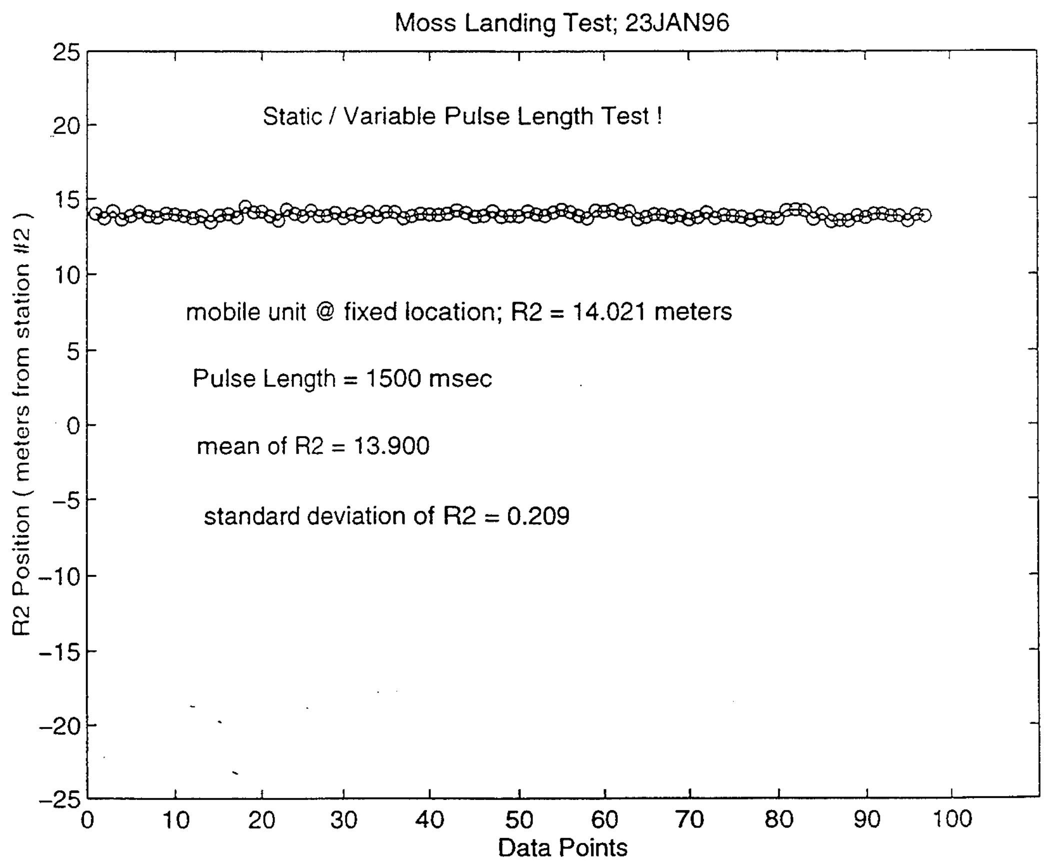


Figure 99. R2 Position Data for Test #160.

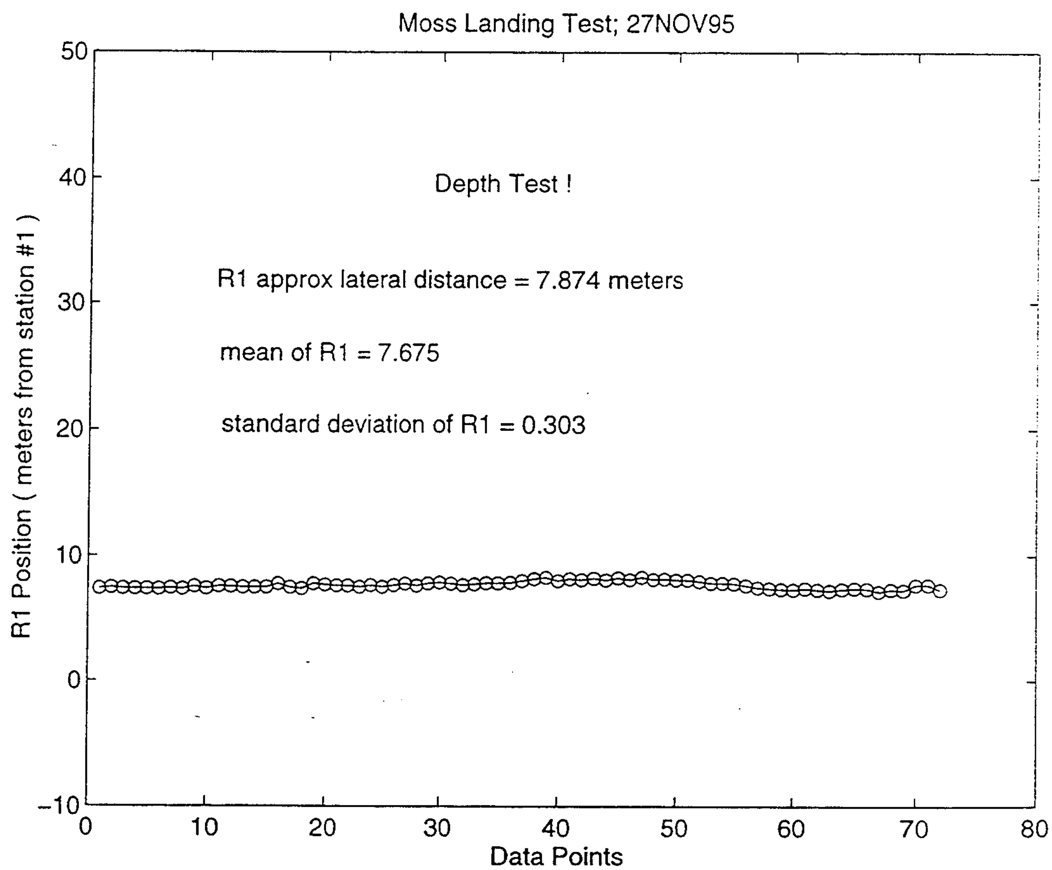


Figure 100 .R1 Position Data for Test #133.

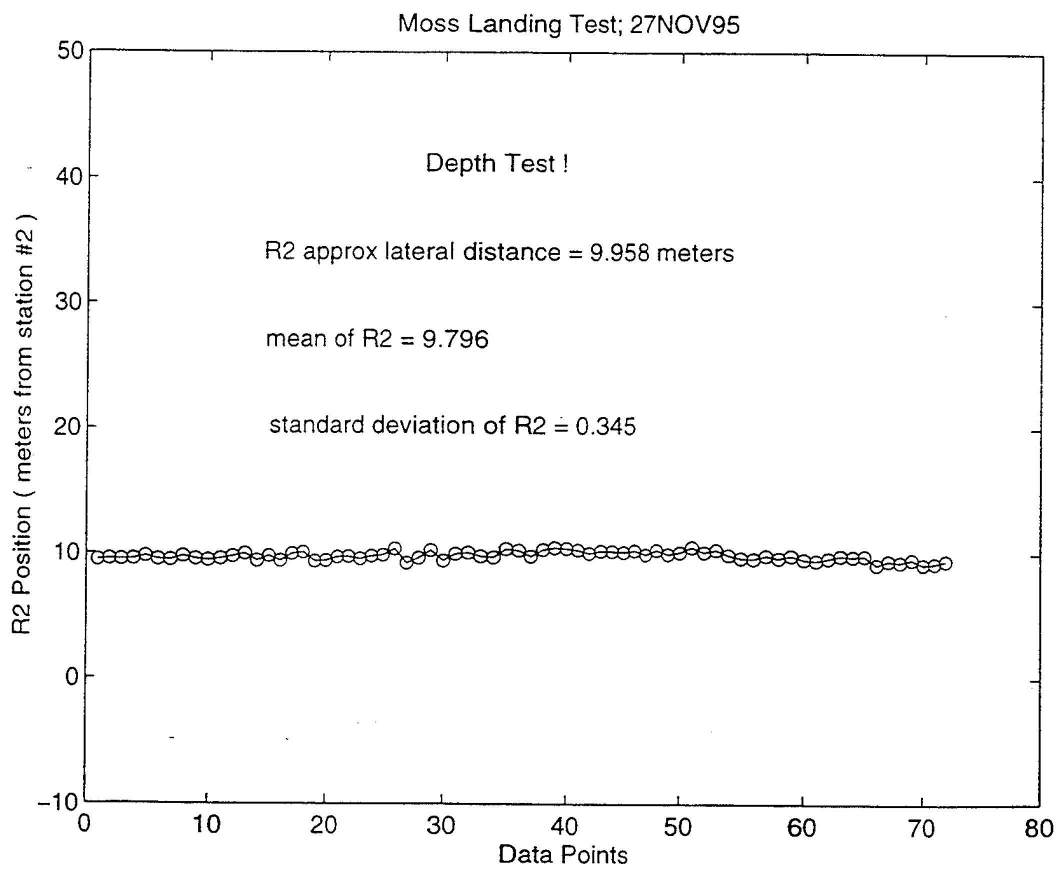


Figure 101. R2 Position Data for Test #133.

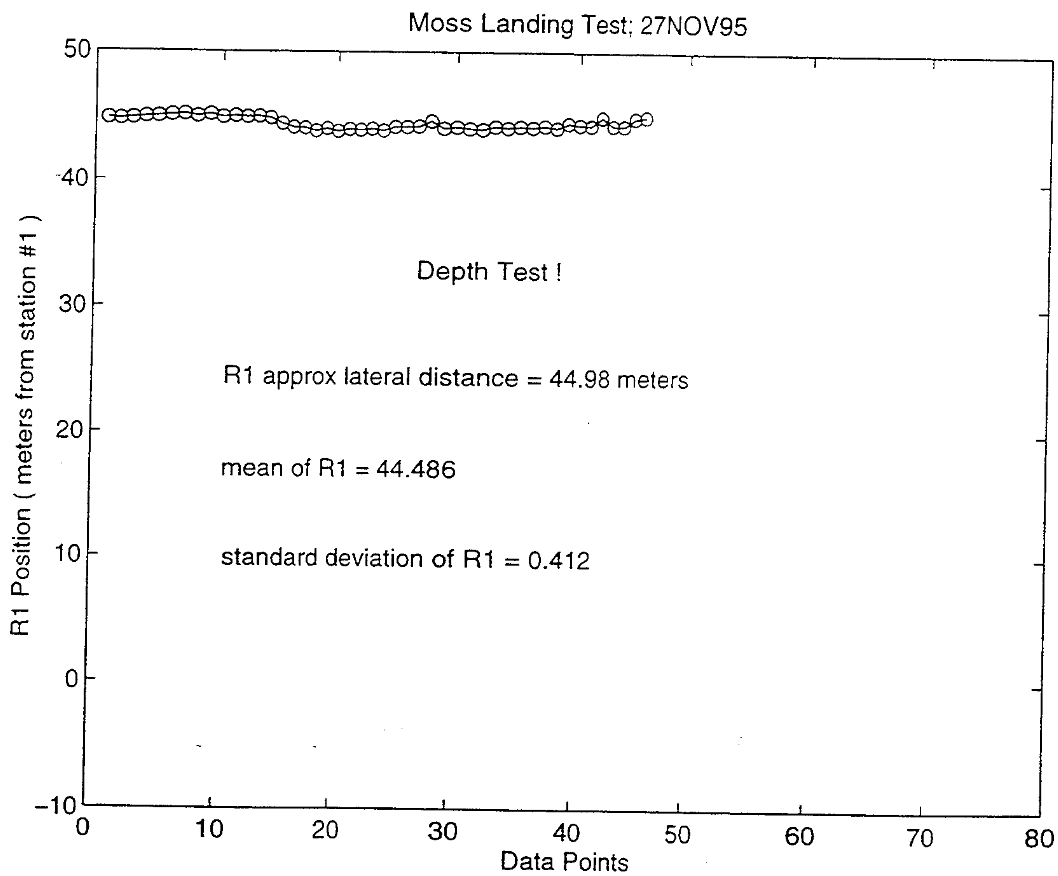


Figure 102. R1 Position Data for Test #139.

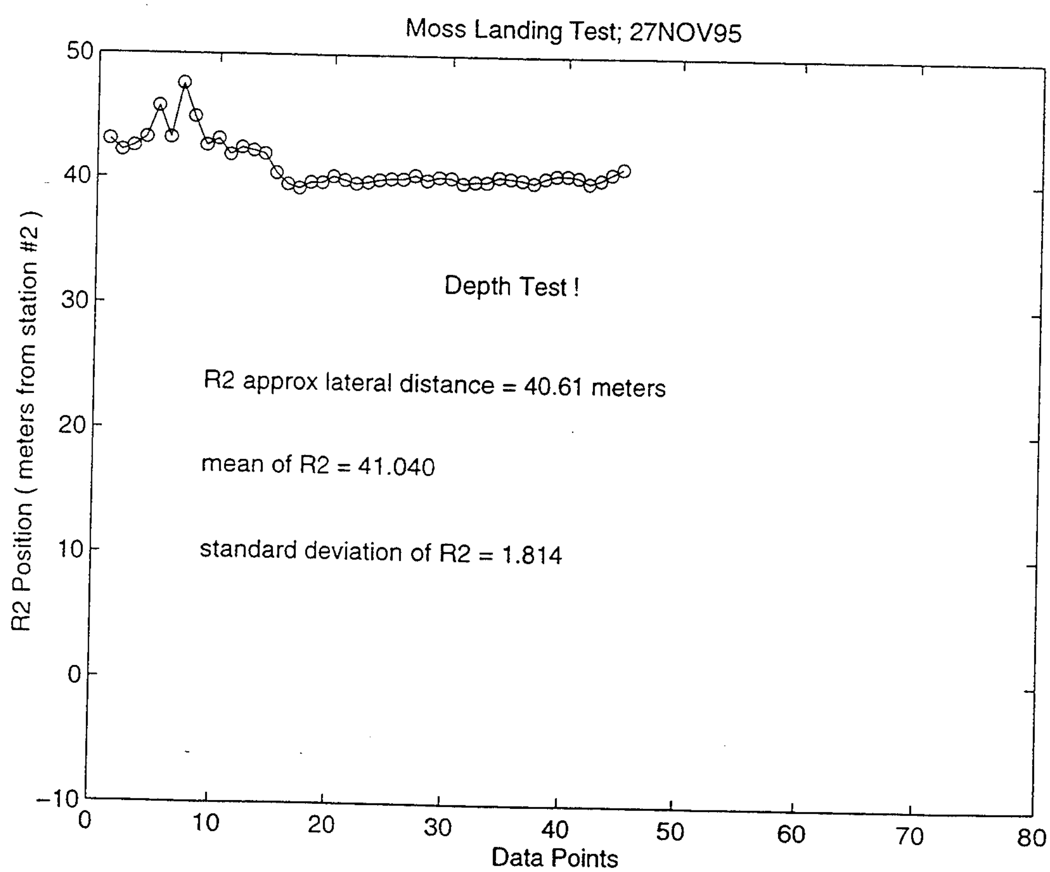


Figure 103. R2 Position Data for Test #139.

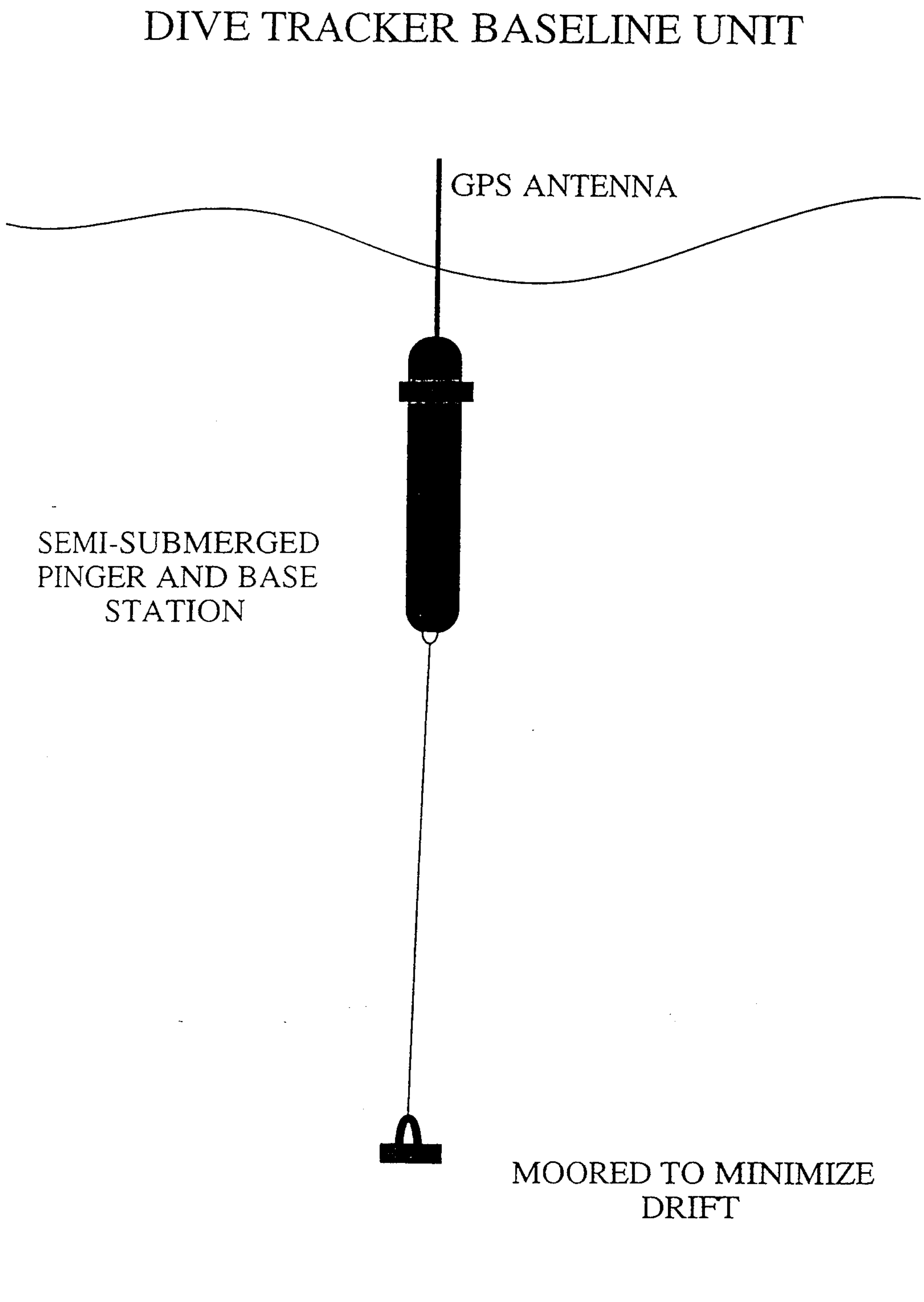


Figure 104. Semi-Submerged Basestation Buoy.

LONG BASELINE ACOUSTICAL SYSTEM

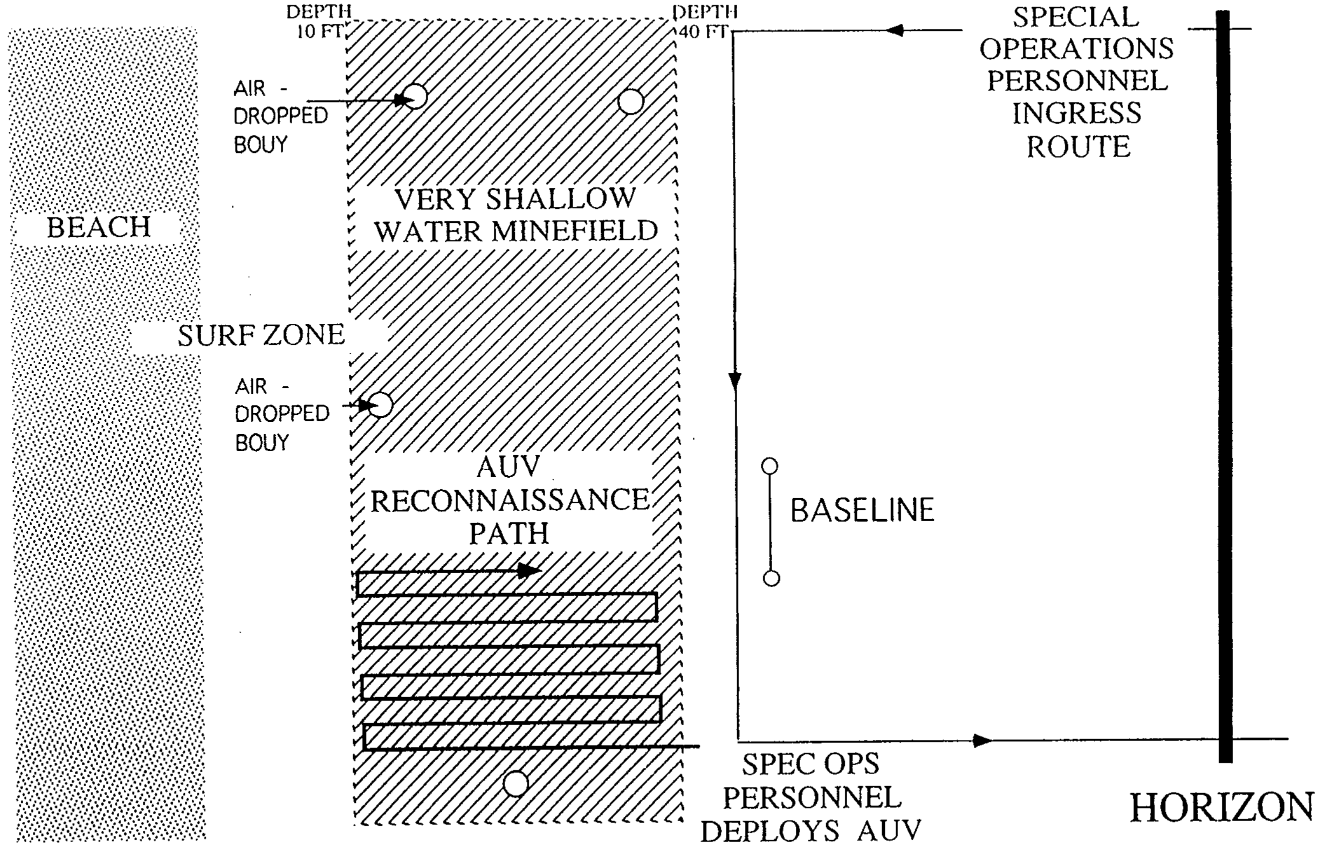


Figure 105. Long Base Line Deployment Scheme.

APPENDIX B. COMPUTER PROGRAMS

Feb 7 1996 15:17:01 matmoss.m Page 1

```
% Jerry Zinni AUV Theisis of Divetracker Navigation System
% This is a matlab m file to plot moss landing experiments

% prior to running this m-file you must load jerry##.out file
% in Matlab from the mosstest directory
% note the required update of file name in the r1 declaration...

 r1 = jerry94(:,1);

% inches to meters conversion...

 rr1 = (1/12)*(0.3048)*r1 ;

% plotting...

 plot(rr1,'-')
 hold
 plot(rr1,'o')

 title('Moss Landing Test; 01NOV95')
 xlabel('Data Points')
 ylabel('R1 Position ( meters from station #1 )')
 axis([0,100,0,50])

% mean,variance, and standard deviation calculations...

 m1 = mean(r1)
 s1 = std(r1)

 m1m = mean(rr1)
 s1m = std(rr1)
 v1m = cov(rr1);

% Frequently used comments for plots added by gtext commands..

  gtext('Dynamic Test !')
% gtext('Static Test !')
% gtext('Static / Zero Length Test !')
% gtext('Static / Variable Pulse Length Test !')
% gtext('Mobile unit attached to row boat')
% gtext('mean of R1 = m1m')
% gtext('standard deviation of R1 = s1m')
%  gtext('mobile unit @ fixed location: R1 = 6.909 meters')
%  gtext('baseline length = 9.14 meters ( 30 feet )')

% Additional gtext comments...

%  gtext('Depth Test !')
%  gtext('R1 approx lateral distance = 44.98 meters')
% gtext('location of R1(@t=0) = 0')
% gtext('location of R1(@t=tfinal) = 444')
% print_hp1
% gtext('possible pier masking problem/slow update rate')
% gtext('lost track completely @ r1 = 3424')
% gtext('boat moving parallel to base line')
% gtext('boat moving away from the base line')
% gtext('(Note;moving around fixed object in the way)')
% gtext('Pulse Length = 1500 msec')
```

Program 1. MATLAB Code "matmoss.m".

```
% Jerry Zinni AUV Theisis of Divetracker Navigation System
% This is a matlab m file to plot histograms of moss landing experiments

% prior to running this m-file you must load jerry##.out file
% in Matlab from the mosstest directory
% note the required update of file name in the r1 declaration...

 r1 = jerry122chop(:,1);

% inches to meters conversion...

 rr1 = (1/12)*(0.3048)*r1 ;

% mean,variance, and standard deviation calculations...

 m1 = mean(r1) ;
 s1 = std(r1) ;
 m1m = mean(rr1)
 s1m = std(rr1)
 v1m = cov(rr1) ;

% Historgram plotting ...
% note the required update of # data points and bandwidht in HN1 declaration.
% note the required update of DiveTracker mean value in the gtext line.

  [N1,X1] = hist(rr1,10);
  HN1 = (N1.*(1/110))*(1/0.08) ;
  [XX1,YY1] = bar(X1,HN1);
  plot(XX1,YY1)

 title('Histogram of Data Points with Gaussian Overlay')
 xlabel('R1 Position ( meters from station #1 )')
 ylabel('Probability Bandwidth ( % / meters )')
 gtext('DiveTracker R1mean = 65.660 meters')
 hold

% Guassian overlay calculations and plotting...
% note the required update of # data points in the j declaration...

 j = 1:1:110;
 p(j) = ( 1/( (sqrt(2*pi))*s1m ) ) * ( exp( - ((rr1(j)-m1m).^2)/(2*(s1m.^2)) ) );
 plot(rr1,p,'*')
```

Program 2. MATLAB Code "mosshis.m".

```
/*
 * DiveBase Default Mission Parameter File
 *
 * This file defines DiveBase operational parameters when operating in
 * real-time mode or in replay mode when no mission specific parameter file
 * is available.
 *
 * Each command must be preceded by the 'at' symbol and ends at the end of
 * the line. (We can't print the 'at' symbol here, otherwise what follows
 * would be interpreted as a command).
 *
 * Author:  Marco Flagg
 * Date:    April 30, 1995
 *
 * (C) 1994, Desert Star Systems
 *
 */


/*
 * Station ID list.
 * This list defines valid station ID codes and associates them with a
 * station symbol and name.  The station symbol is used to identify a
 * station on the dive site display.  The station name is used for
 * identification in the various DiveBase data windows.
 * All stations must use the same station ID list to obtain meaningful
 * communication.
 *
 * Command format: A<station ID>:<station symbol> <station name>
 * where:
 * <station ID>:      00..49
 * <station symbol>: Up to three characters
 * <station name>:   Up to nine characters
 *
 */
@A00:S0 SURFACE-0
@A05:D0 PHOENIX

/*
 * Maximum AUV range (feet)
 */
@R: 1000


/*
```

Program 3. DiveBase Configuration File.

```
 * Maximum baseline length (feet)
 */
@L: 100


/*
 * Communication speed:
 * 1. Speed:
 *    0: 3.6 nibbles/sec (14.2 baud)
 *    1: 8.9 nibbles/sec (35.7 baud)
 *    2: 17.9 nibbles/sec (71.4 baud)
 *    3: 35.7 nibbles/sec (142.8 baud)
 * 2. Receive<->Transmit Turn-around 'quiet' period: 0 - 999999 microseconds
 */
@S:1 125000


/*
 * Data exchange parameters:
 * 1. Receiver gain: 0 (least sensitive) - 3 (most sensitive)
 * 2. Detection threshold: 0 (most sensitive) - 127 (least sensitive)
 * 3. Transmit power: 0 (least power) - 127 (most power)
 * 4. Pulse length: 0 - 9999 microseconds
 */
@X: 2 16 127 4000

/*
 * Distance measurement offset compensation (inch)
 * The indicated value is subtracted from any distance measurement
 */
@C: 36

/*
 * Serial data transmission by diver or ROV/AUV station:
 * 1. Transmit 'raw' position data via serial link: 1=YES, 0=NO
 * 2. Transmit X-Y-Depth position data via serial link: 1=YES, 0=NO
 * 3. Transmit message data via serial link: 1=YES, 0=NO
@Z: 1 0 1


/*
 * Station function:
 * 0: Diver station
 * 1: Surface station
 * 2: Remote stations
```

Program 3. DiveBase Configuration File (continued).

```
*/
@F:0

/*
 * Station ID:
 * Surface station: 0
 * Remote stations: 0-3
 * Diver Stations: 0-9
 */
@I:0

/*
 * Network type & navigation protocol:
 * 1. Network type:
 *   0: Single transducer surface station only
 *   1: Dual transducer surface station
 *   2: Single transducer surface station & 1 remote station
 *   3: Single transducer surface station & 2 remote stations
 *   4: Single transducer surface station & 3 remote stations
 *   5: Single transducer surface station & 4 remote stations
 * 2. Address mode:
 *   0: One diver station only (ping inquiry)
 *   1: More than one diver station (address code inquiry)
 * 3. Diver telemetry:
 *   0: Diver station sends no telemetry
 *   1: Diver station sends 2-channel telemetry (depth & air)
 * 4. Navigation data availability:
 *   0: Navigation data is available to surface station only
 *   1: Navigation data is available to surface and diver stations
 */
@N:1 0 0 1

/*
 * Number of divers to be inquired: 0-9
 */
@#:1

/*
 * Remote station locations (stations 0-3):
 * 1. Range (ft)
 * 2. Bearing (degrees)
 * 3. Depth (ft)
 *
```

Program 3. DiveBase Configuration File (continued).

```
 * note: Set all parameters to 0 for auto-survey
 */
@r0: 48 0 0
@r1: 0 0 0
@r2: 0 0 0
@r3: 0 0 0


/*
 * Operation side of baseline (used in network types 1 & 2):
 * 0: right
 * 1: left
 *
 */
@b:1


/*
 * Surface station transducer depth (feet)
 */
@d:0

END
```

Program 3. DiveBase Configuration File (continued).

Feb 9 1996 09:20:31 **addtimemod.m** Page 1

```
%matlab script to generate time for Moss Landing data taken without time marks
%Time difference based on combined range and speed of sound in water of 4800fps
%Time based on 4 ping cycle and 1e5 microsecond rest period.
%Program converts data taken in inches to meters
%Time is in seconds
%
function [trm]=addtimemod(d)
%
dm=d.*2.54e-2;  %convert inches to meters
r=size(d);
t(1)=0;
for i=2 : r
        t(i)=t(i-1)+(3*d(i-1,1)+d(i-1,2))/1463.04+4*125000e-6;
end
trm=[t' dm];
```

Program 4. MATLAB Code "addtimemod.m".

```
% Matlab m-file functions as a high pass filter
% removes vehicle motion and keep DiveTrackernoise.
%       Based on kalman filter provided by Dr. A. Healey
%       3 order model for relative motion
%       XD=A*X+B*U+Q; Y=C*X+V, needs t and y
%       Plots estimated range rate as used in the vehile
%       and estimated range rate as designed in the mfile
%       using experimentalrange data.
%
%    Q is the system noise variance and R is the measurement noise variance
%       Data is input matrix of time vector and range vector

% Load data file and add time vector...

 load jerry94.out
 [in]=addtimemod(jerry94);

% Assign variables...

d=in;    %input file
t=in(:,1);       %       t is the Time vector
y=in(:,2);       %Y is the Range vector
A=[0, 1, 0; 0, 0, 1; 0, 0, 0];
Q=0.0001;
B=[0;0;1];
C=[1,0,0];
D=0;
%[phi,gam]=c2d(A,B,0.1);  Removed due to changing time step
R=1000;
pk=diag([1e-1,1e-1,1e-1]);
xk=zeros(3,size(t));
G=xk;
err=zeros(1,size(t));
%
xk(1,1)=y(1);    %Set initial Range to First data point
for i=2:size(t);
        dt=t(i)-t(i-1); %Determine time step for each interval
        [phi,gam]=c2d(A,B,dt);  %Calculate new for each time step
        xk1=phi*xk(:,i-1);
        pt=phi*pk*phi'+gam*Q*gam';
                G(:,i)=[pt*C'*inv(C*pt*C'+R)];
        err(i)=[y(i)-C*xk1] ;
%       errt(i)=err(i)';

        if abs(err(i)) > 20.0
                err(i) = 0;
        end
%
%       err is the residual high frequency errors as deviations from the best
%       low frequency estimate of the motion
%

        xk(:,i)=xk1+G(:,i)*err(i);
%
% xk(:,i) is best estimate of low frequency for each of 3 states of the ith time ste
p
%
        pk=[eye(3)-G(:,i)*C]*pt;
        psave(1,i)=pk(1);
        psave(2,i)=pk(2);
        psave(3,i)=pk(3);
end             %       Ends for loop
%
 phic=[phi-G(:,10)*C];
 Lamda=eig(phic);
 zeta=real(Lamda)./abs(Lamda);
 [m,ph,w]=dbode(phic,G(:,10),[0,1,0],D,0.1);

 high=xk;

 % Plotting...plot raw data -vs-time and filtered data -vs- time

  figure,plot(in(:,2),'o')
```

Program 5. MATLAB Code "highfilterr.m".

```
 hold
 plot(xk(1,:),'x')
 plot(xk(1,:),'-')
 legend('Raw Data','Filtered Data')
 title('Filtered Moss Landing Test; 01NOV95')
 xlabel('Data Points')
 ylabel('R1 Position ( meters from station #1 )')

 figure,plot(err)
 hold
 plot(err,'x')
 axis([0,100,-3,3])
 title('Error from Moss Landing Test; 01NOV95')
 xlabel('Data Points')
 ylabel('R1 High Frequency Info ( meters )')

 r1mean = mean(in(:,2))
% r1mean = mean(xk(1,:))
 hfstddev = std(err)

% gtext('Mean R1 Position = r1mean meters')
% gtext(' HF Standard Deviation = hfstddev')
```

Program 5. MATLAB Code "highfilterr.m" (continued).

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